EVOLUTION OF KEPLER PLANETS

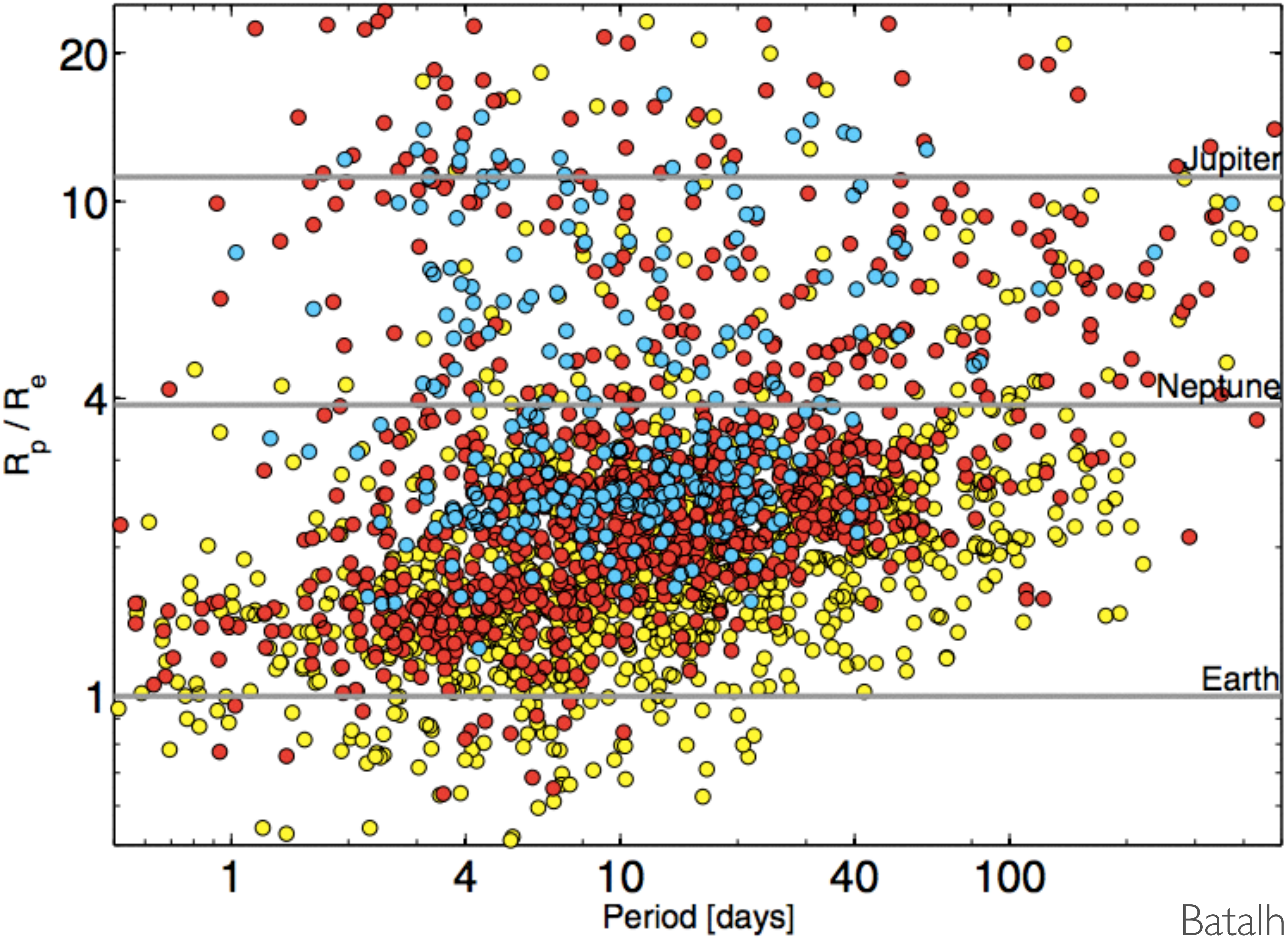
James Owen (CITA)

Yanqin Wu (University of Toronto)
Alan Jackson (Arizona State)
Fred Adams (University of Michigan)

CITA
ICAT
Canadian Institute for
Theoretical Astrophysics
L'institut Canadien
d'astrophysique theorique

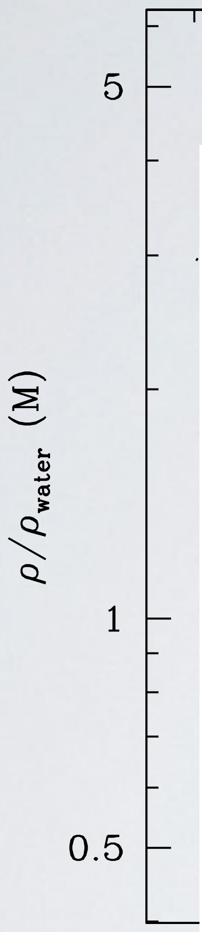
ISIMA, CITA 23rd July 2014

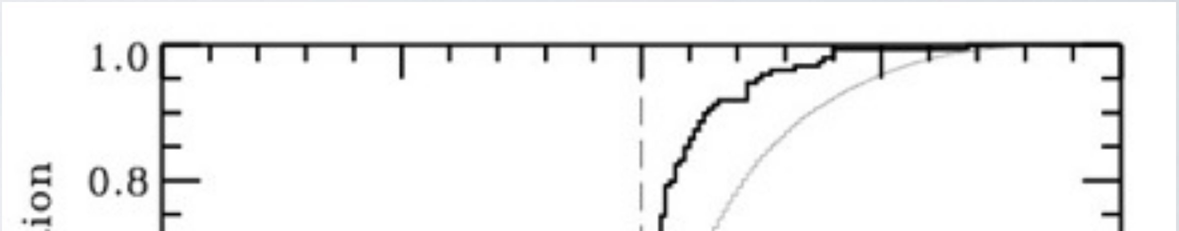
MOTIVATION



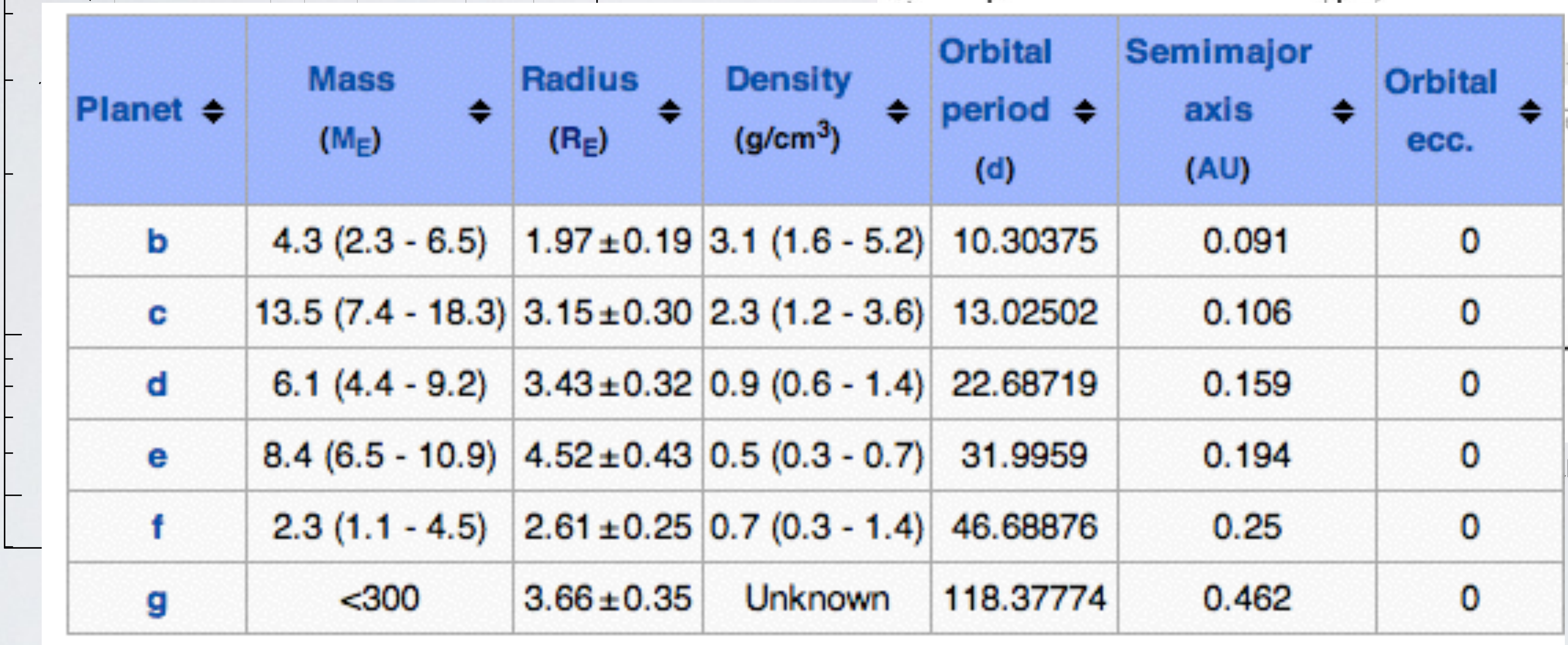
Batalha et al. (2013)

OBSERVATIONAL CLUES

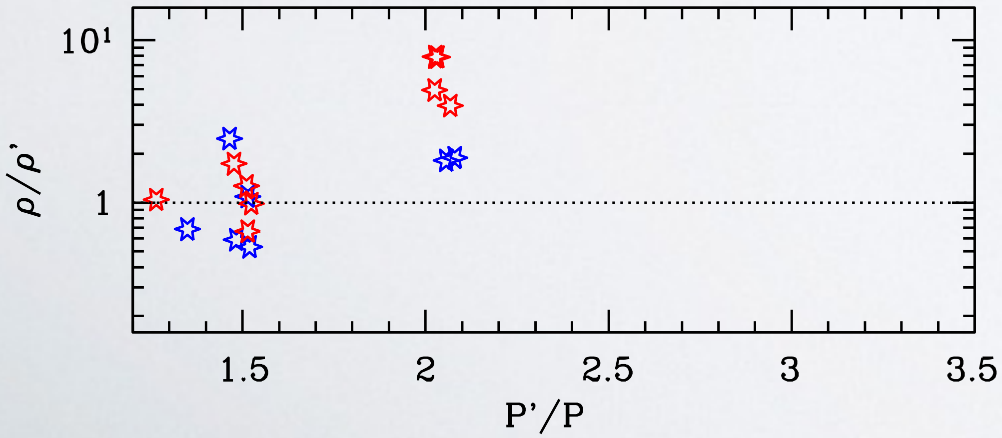


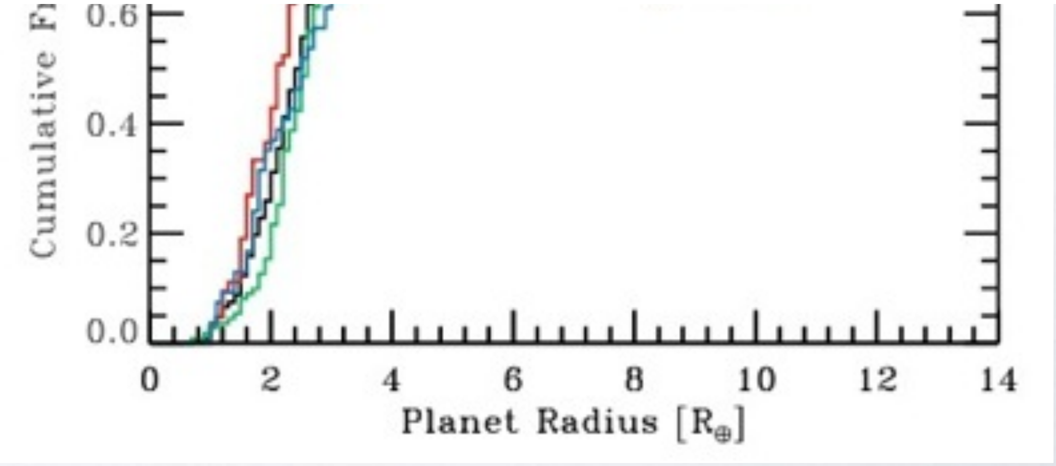


l. 2012



Planet	Mass (M_E)	Radius (R_E)	Density (g/cm^3)	Orbital period (d)	Semimajor axis (AU)	Orbital ecc.
b	4.3 (2.3 - 6.5)	1.97±0.19	3.1 (1.6 - 5.2)	10.30375	0.091	0
c	13.5 (7.4 - 18.3)	3.15±0.30	2.3 (1.2 - 3.6)	13.02502	0.106	0
d	6.1 (4.4 - 9.2)	3.43±0.32	0.9 (0.6 - 1.4)	22.68719	0.159	0
e	8.4 (6.5 - 10.9)	4.52±0.43	0.5 (0.3 - 0.7)	31.9959	0.194	0
f	2.3 (1.1 - 4.5)	2.61±0.25	0.7 (0.3 - 1.4)	46.68876	0.25	0
g	<300	3.66±0.35	Unknown	118.37774	0.462	0





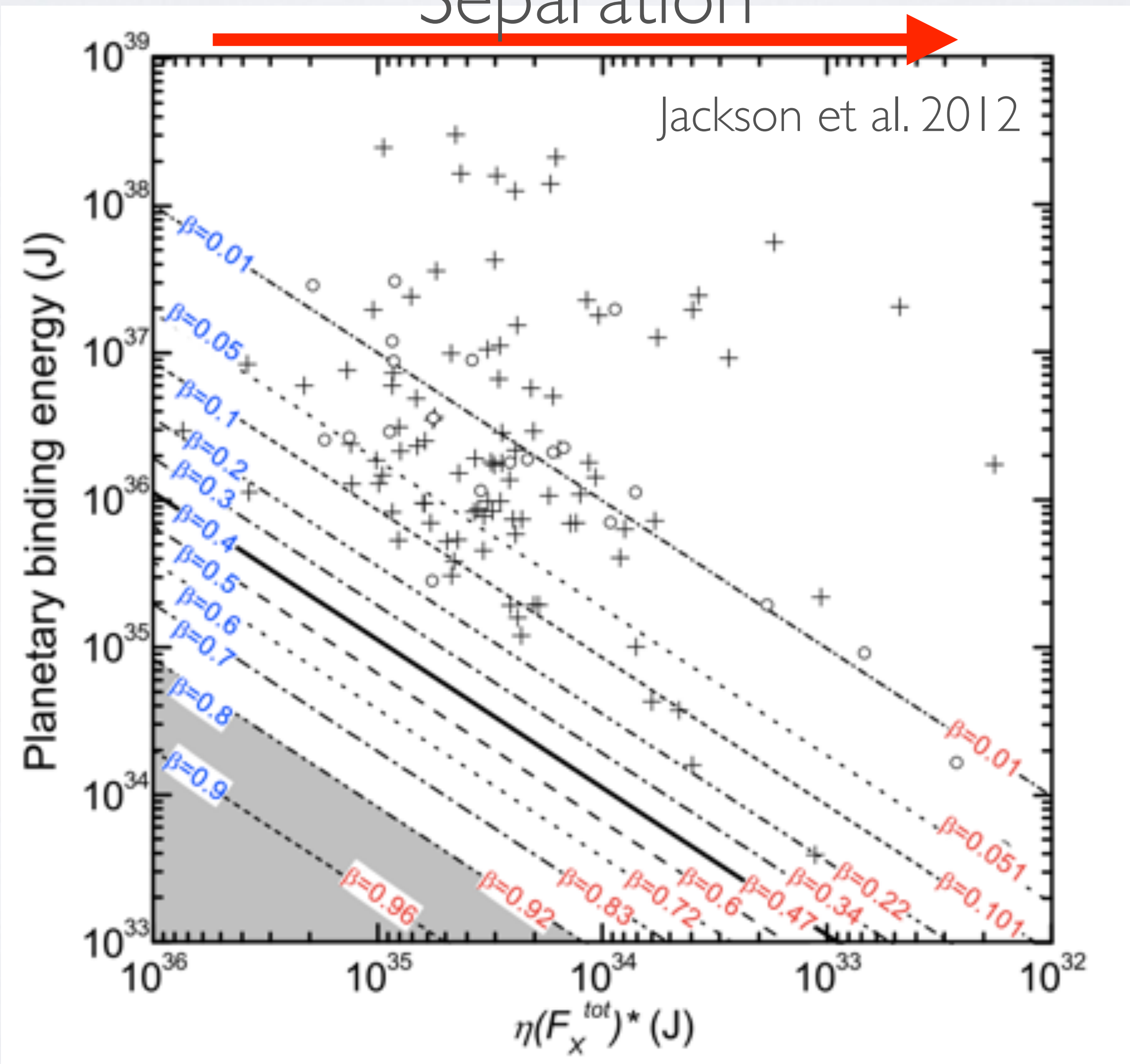
BUT...

- Is it Nature or Nurture...
- Are the differences we see in the planet population today an imprint from birth - so we can learn something about planet formation.
- Or has some-other the dominant sculpting process that is driving the differences we see today? Evaporation?

MOTIVATION FOR EVAPORATION

- EUV & X-rays can heat upper atmosphere to the ~10,000K ~ escape temperature for planets.

- High energy received for close in planets comparable to their gravitational binding energy (Lecavelier des Etangs 2007, Davis & Wheatley 2009)



Separation

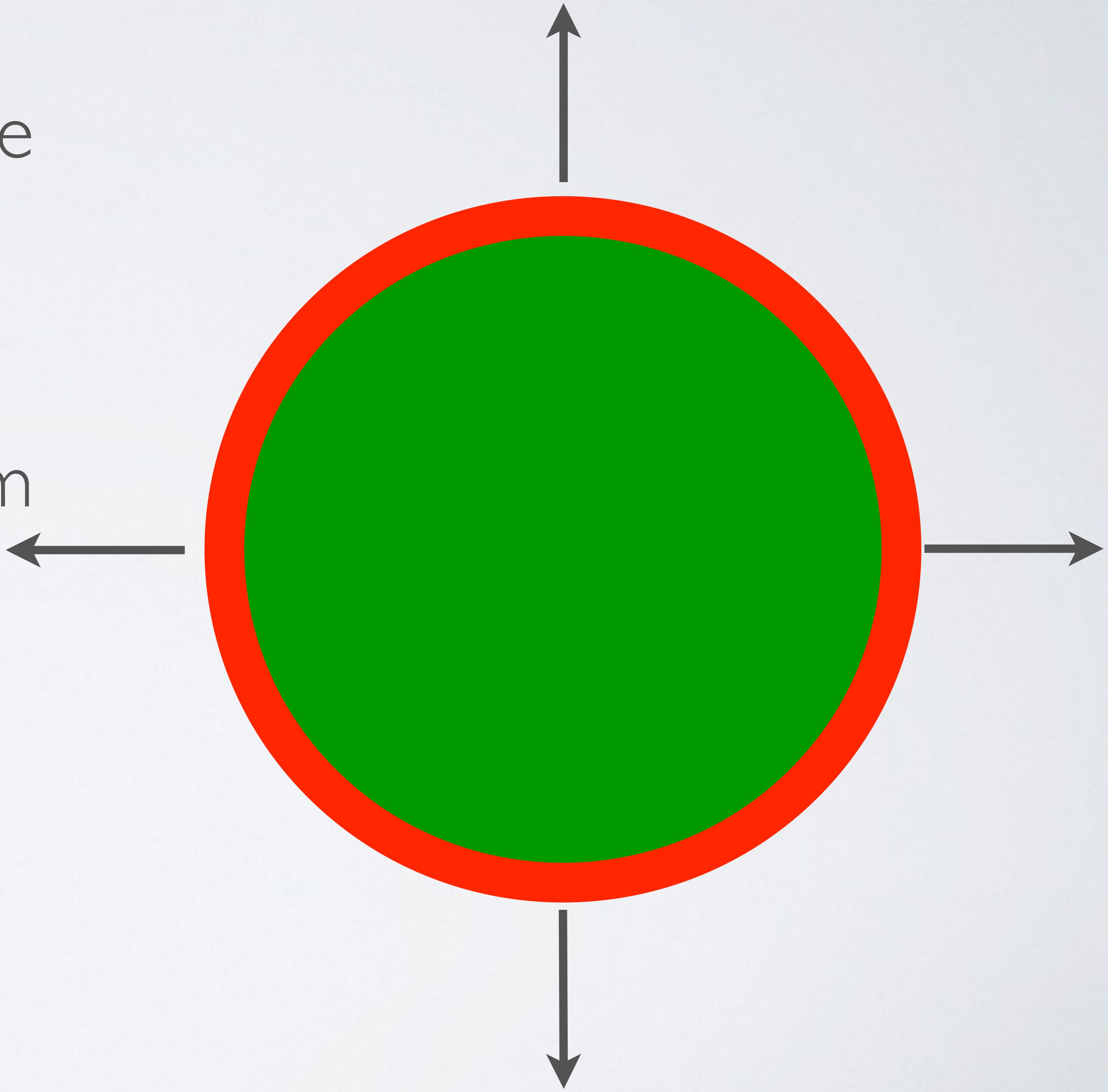
Jackson et al. 2012

A SIMPLE MODEL FOR HYDRODYNAMIC ESCAPE

- Heat-up the surface of the planet's atmosphere.
- This heated region then expands and escapes from the planet.

$$F\pi R_p^2 \mathrm{dt} \sim \frac{GM_p \mathrm{dm}}{R_p}$$

$$\frac{dm}{dt} = \frac{F\pi R_p^3}{GM_p}$$



‘ENERGY-LIMITED EVAPORATION’

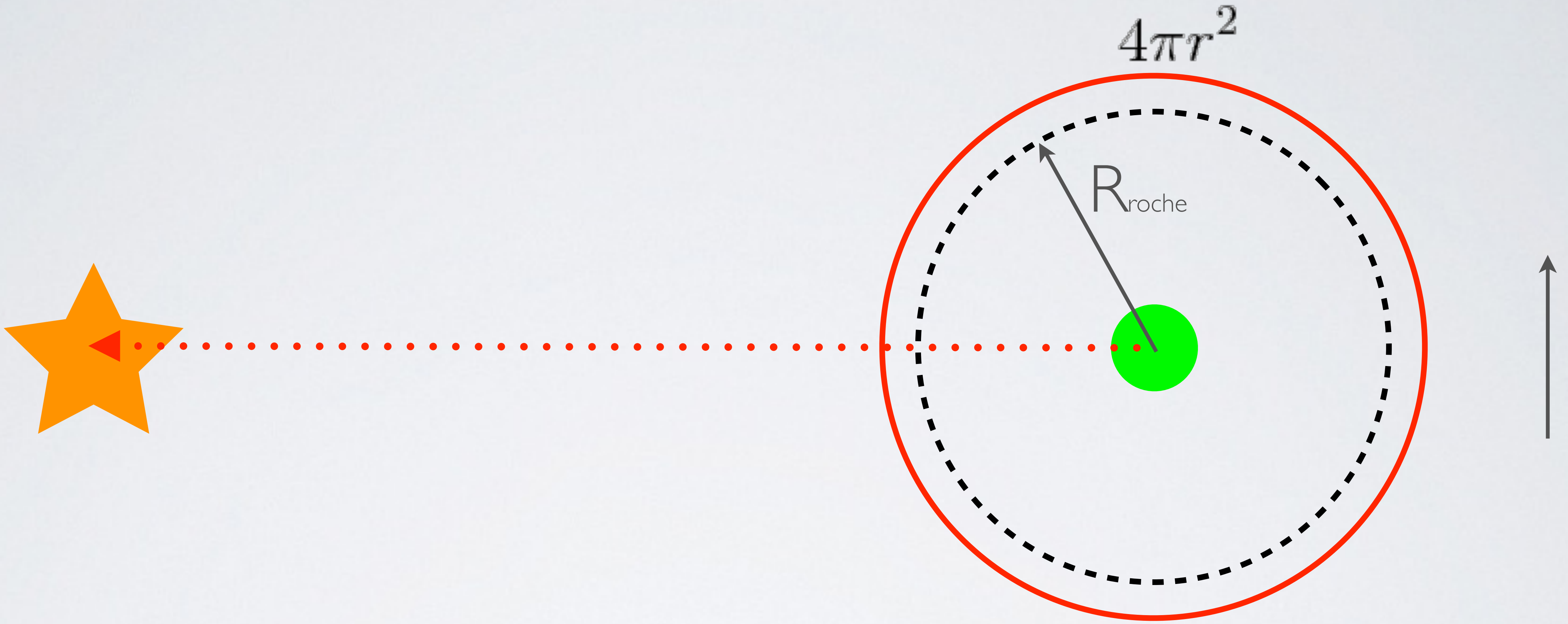
$$\dot{m} = \boxed{\eta}\frac{\boxed{L_{HE}}R_p^3}{3GM_pa^2K(R/R_{\rm roche})}$$

- Apart from detailed models for specific planets (e.g. HD209458b -Yelle et al. 2004; Tian et al. 2005; Garcia Munoz 2007; Murray-Clay et al. 2009...), planetary evaporation typically considered in energy limited formalism (e.g. Watson 1981 Lammer 2003,2009; Erkaev et al. 2007 ...)

- Assume every photon is turned into mass-loss at some efficiency.

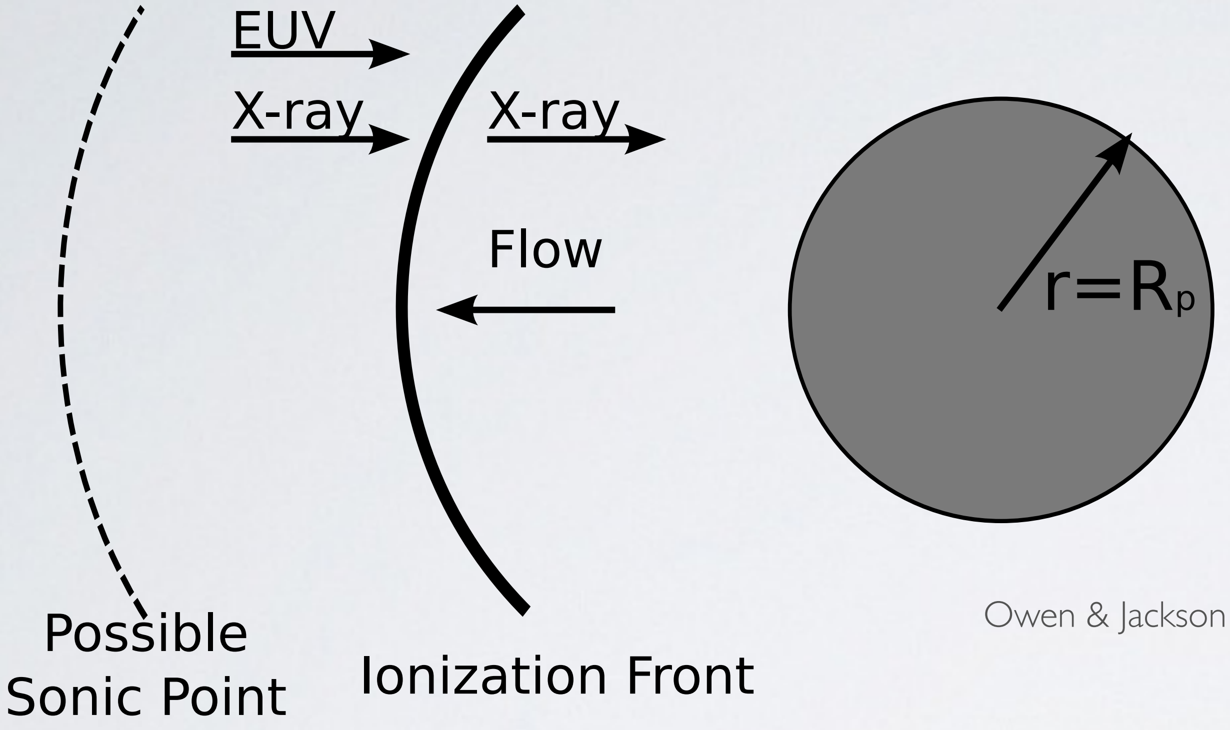
- Questions: What efficiency should I use? Is the flow truly energy limited? Ballistic vs Hydrodynamic ? What is L_{HE}?

1D MODEL SETUP



- Assume spherical divergence along streamline.
- Calculate flow solution by integrating along streamline.
- Check flow in hydrodynamic limit.
- Assume mass-loss equal over full sphere.

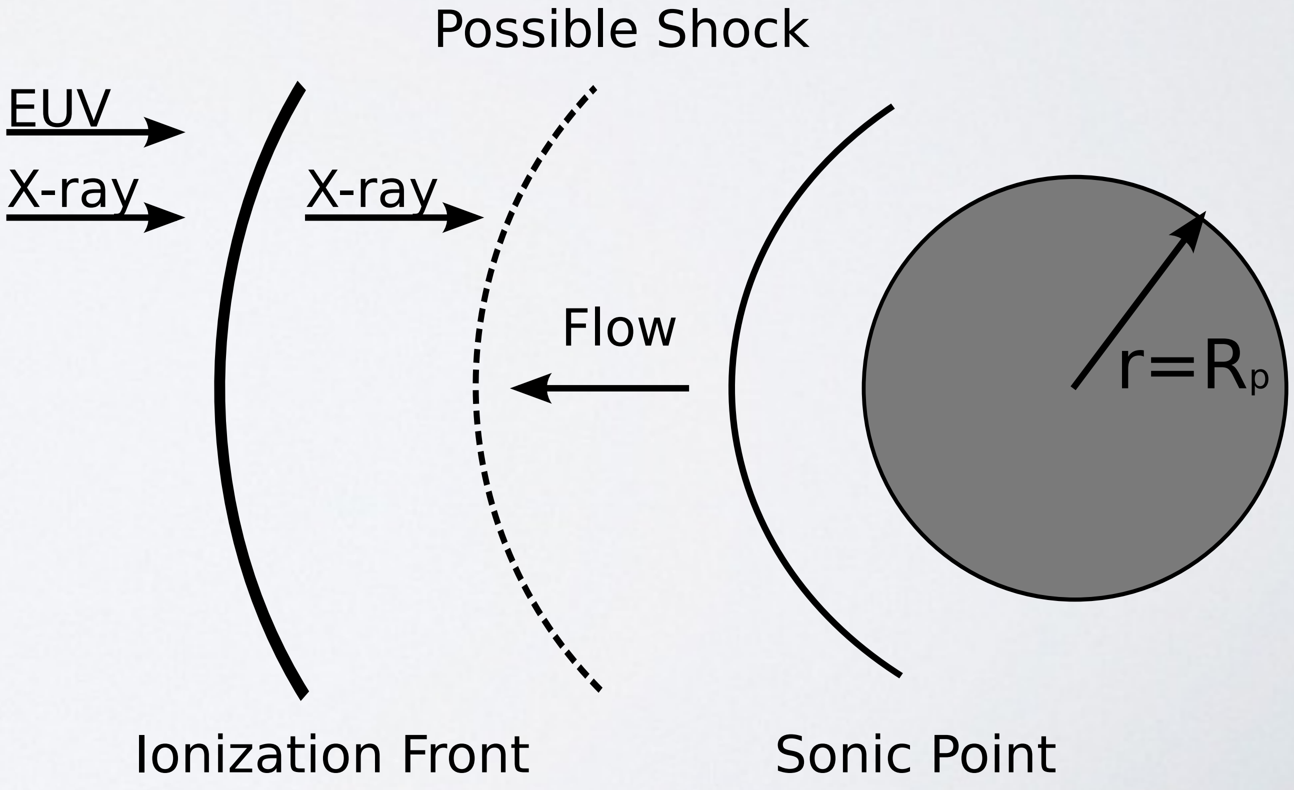
EUV OR X-RAYS



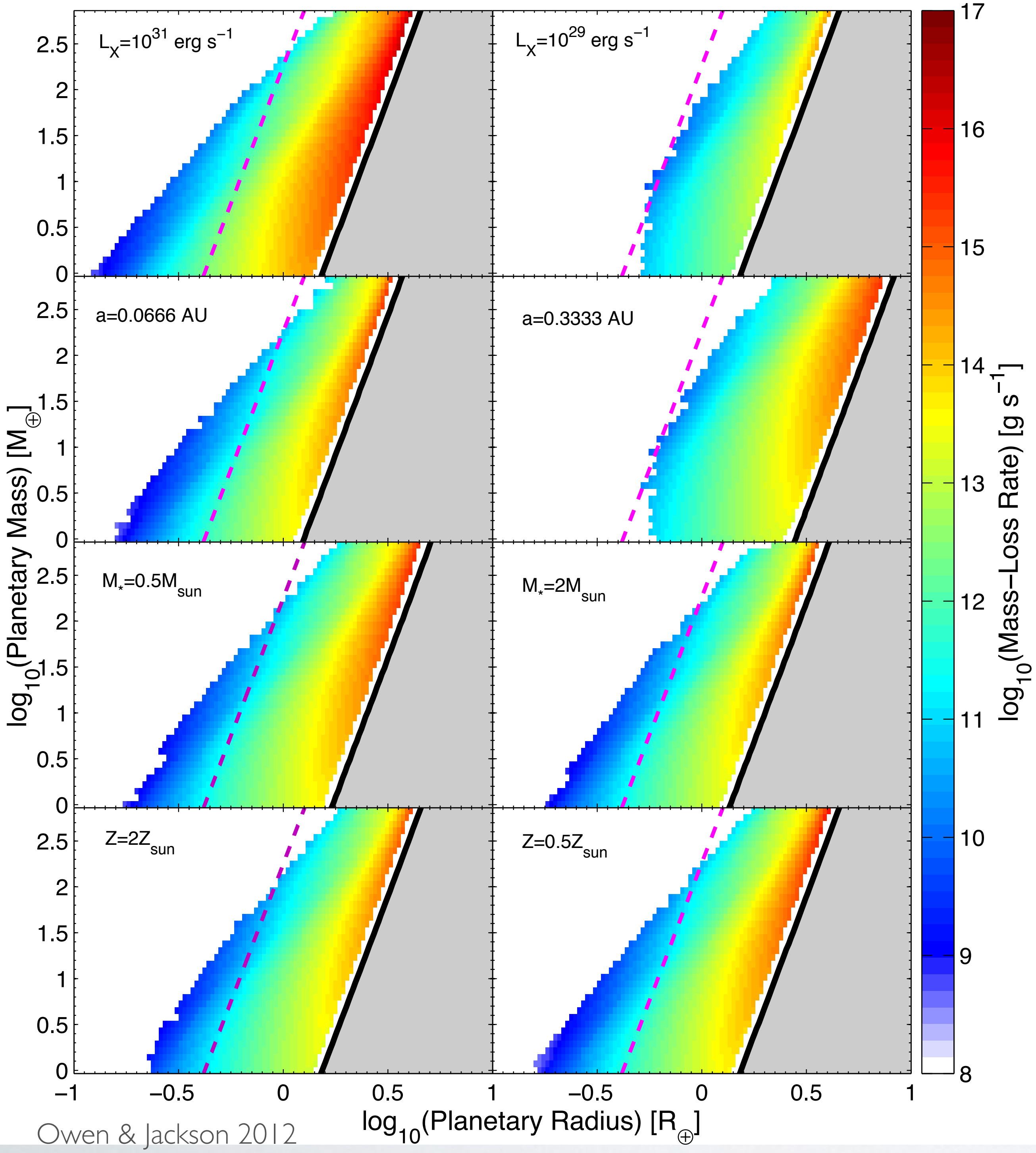
Owen & Jackson 2012

- EUV driven :- flow transitions to supersonic once it enters the EUV heated region

- X-ray driven :- flow transitions to supersonic in the X-ray heated region.



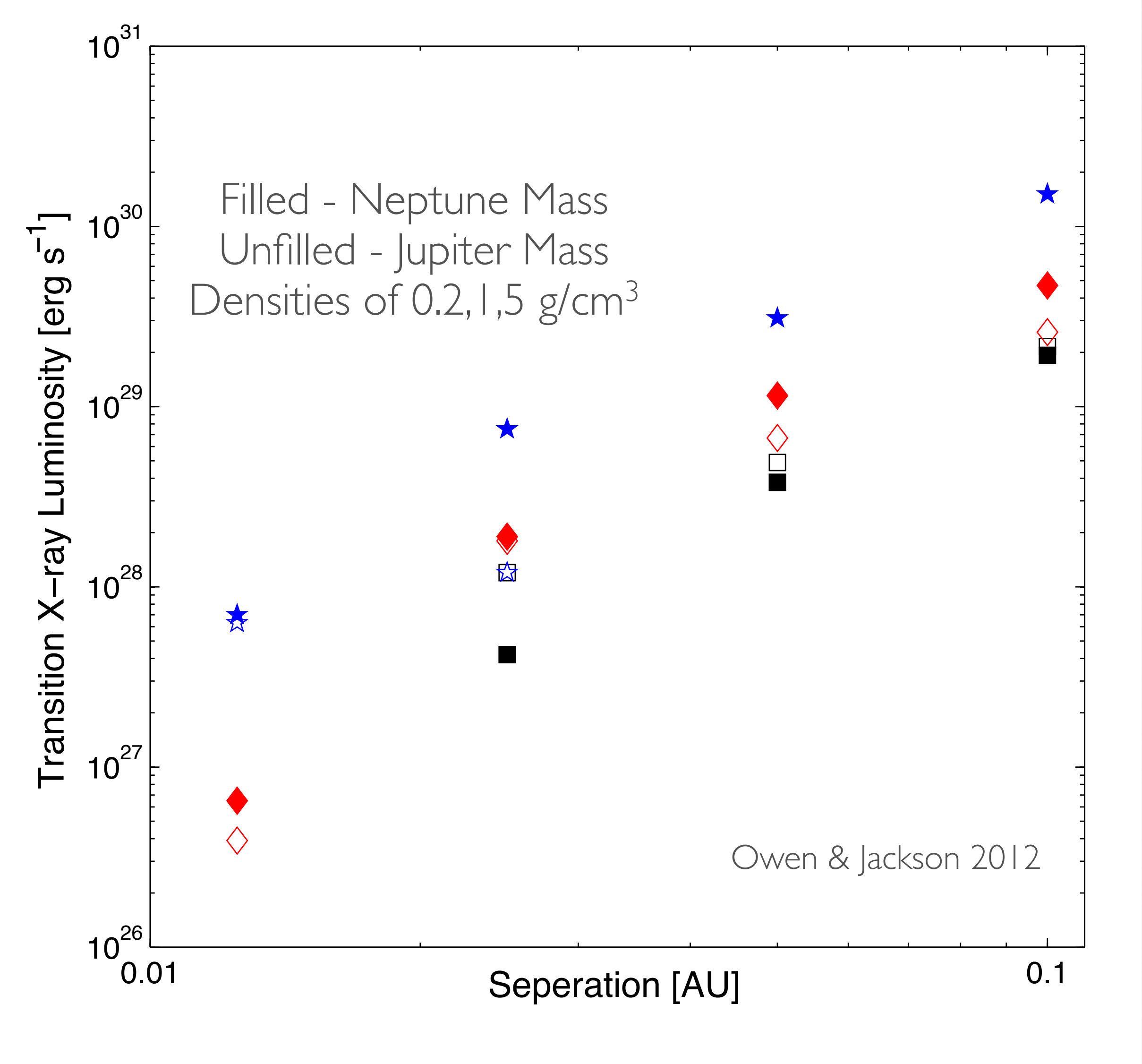
HYDRODYNAMIC EVAPORATION: MASS-LOSS RATES



Owen & Jackson 2012

- Mass-Loss rates increase with planet mass and radius
- Hydrodynamic evaporation becomes impossible at higher masses.
- Evaporation becomes important at low masses.
- X-ray driven dominates EUV driven at early times.

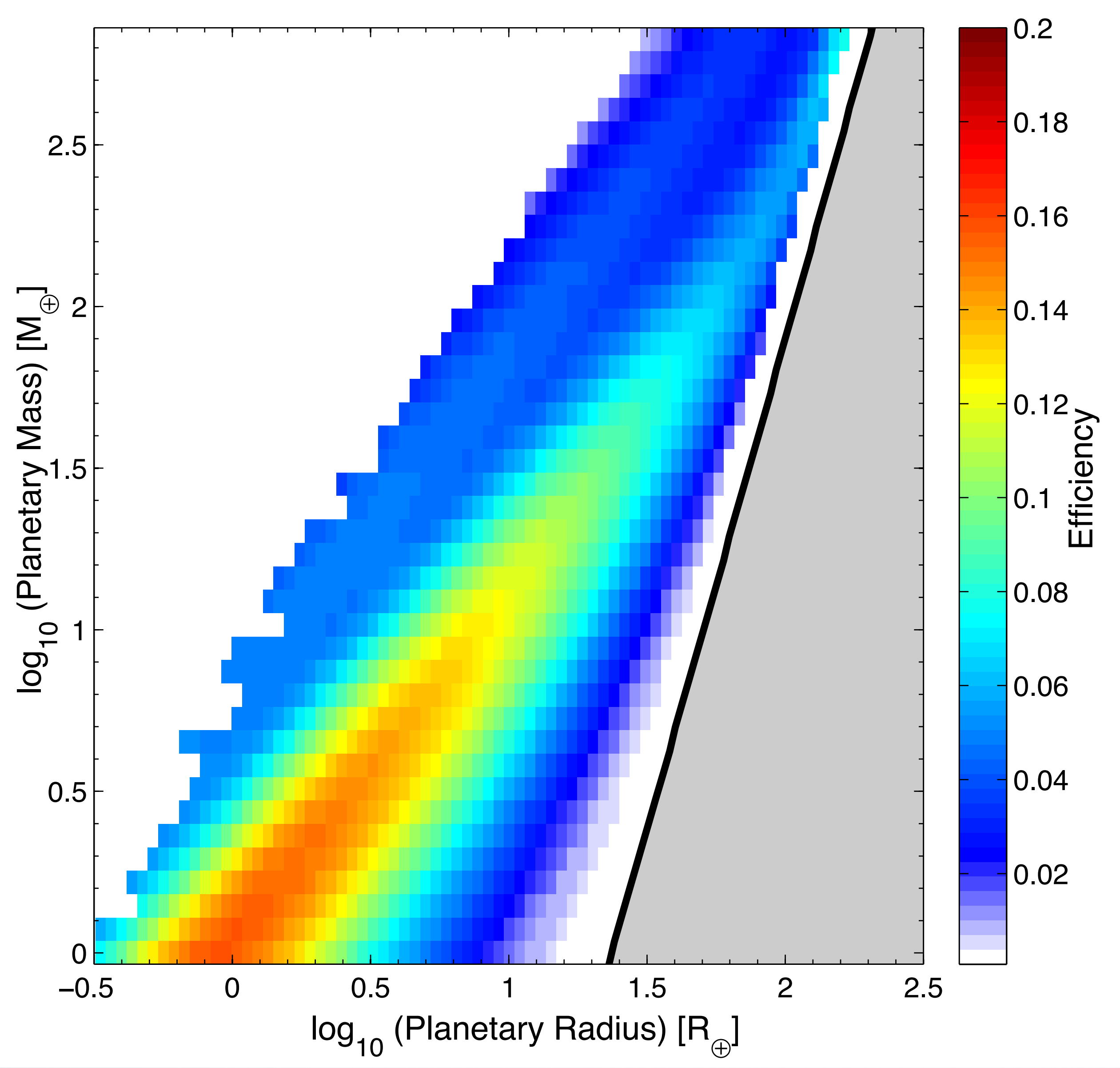
TRANSITION FROM X-RAY TO EUV DRIVEN EVAPORATION



- X-ray luminosity falls with time: 1e30 erg/s at early times, 1e27 at late times.

- As the X-ray luminosity falls, the flow topologies changes and transfers from X-ray driven to EUV driven.

COMPARISONS WITH THE ENERGY LIMITED `EFFICIENCY'

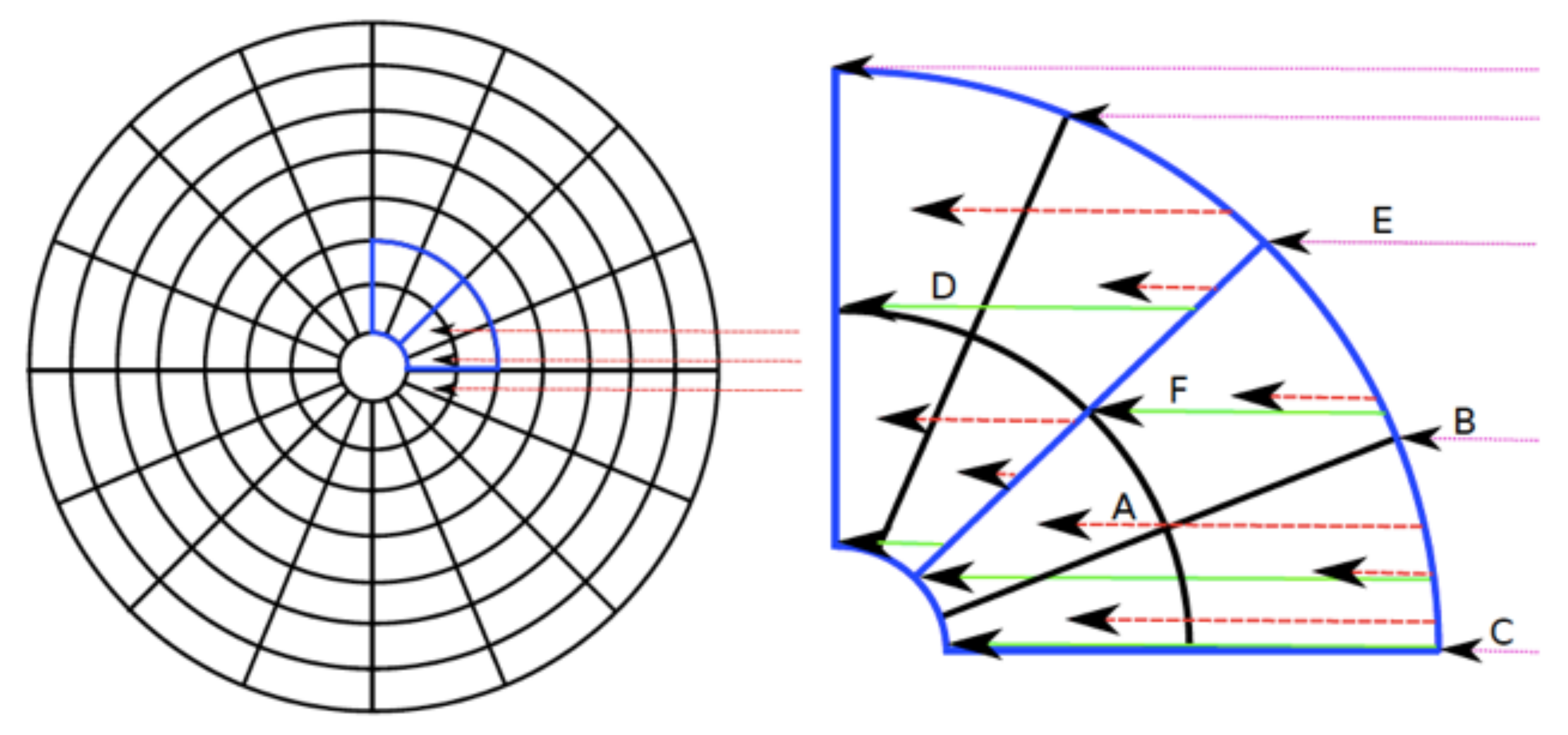


- In general 'efficiency' drops with increasing planet mass, (higher escape velocity + larger radius = longer flow time)

- Radial peak when escape temperature matches gas temperature at base of flow.

- For close-in exoplanets (<0.2 AU) flow is not, in general energy limited and most energy is lost through radiative processes.

NUMERICAL MULTI-DIMENSIONAL CALCULATIONS

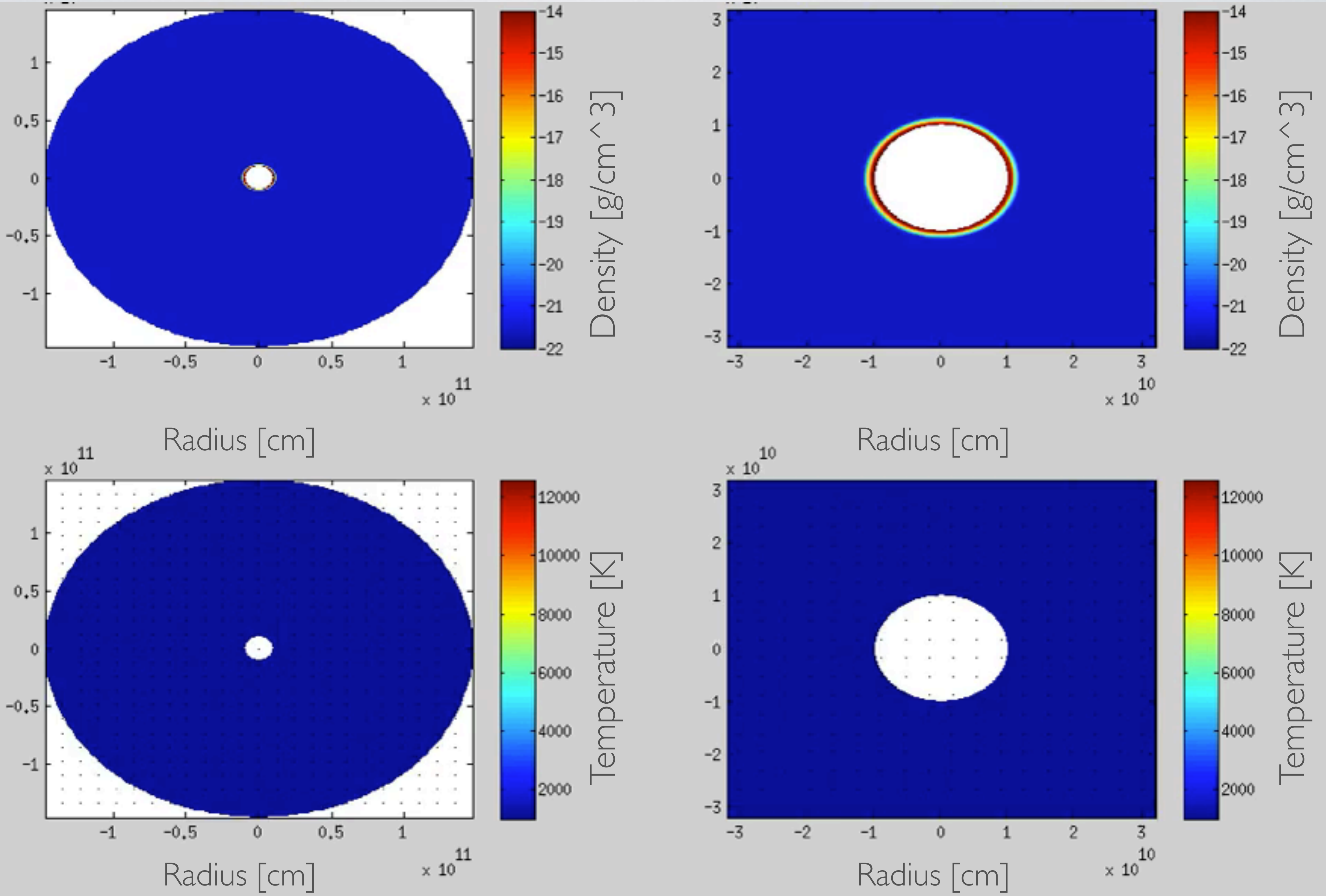


- Developed a combined 1/2/3D (Magneto-)Hydrodynamic and Radiative transfer scheme, build using the ZEUS code.
- Plane parallel UV + X-ray radiative transfer on spherical hydrodynamic grid, based on hybrid characteristics method (e.g. Rijkhorst et al. 2005).
- Time-dependant heating and cooling; ionisation and recombination; multi-species advection.
- `Photon-conserving' so can track R & D type ionisation fronts correctly (c.f. C2RAY - Mellema et al. 2006).

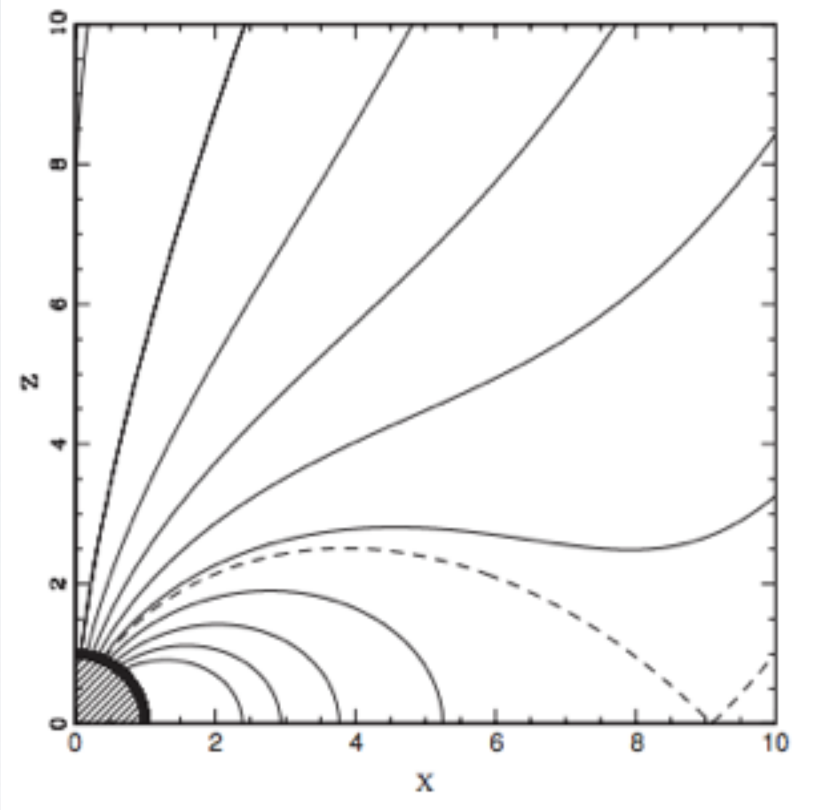
2D HYDRODYNAMIC MODEL

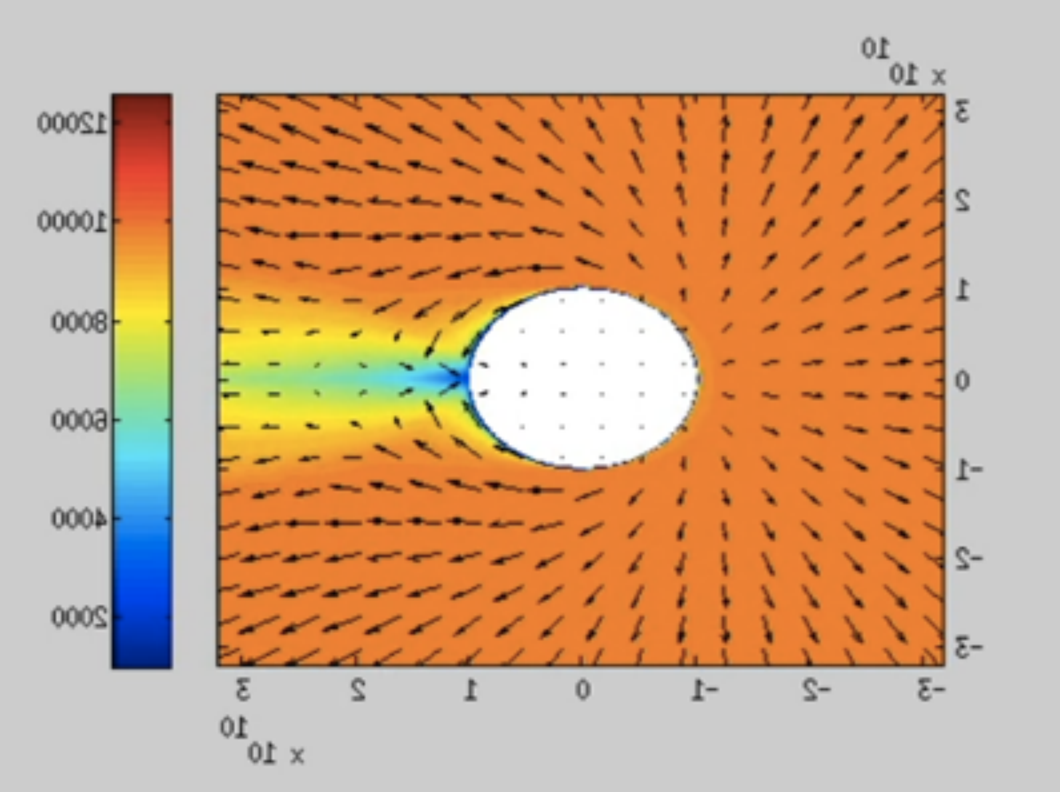
- First 2D hydrodynamic model with realistic radiative transfer.
- For Jupiter mass planet at 0.05 AU around a young sun-like star.
- Grid resolution in upper atmosphere of planet 30km << scale height.
- Pure Hydrogen, non-equilibrium thermodynamics + ionisation balance.

2D HYDRODYNAMIC MODEL



ROLE OF MAGNETIC FIELDS?

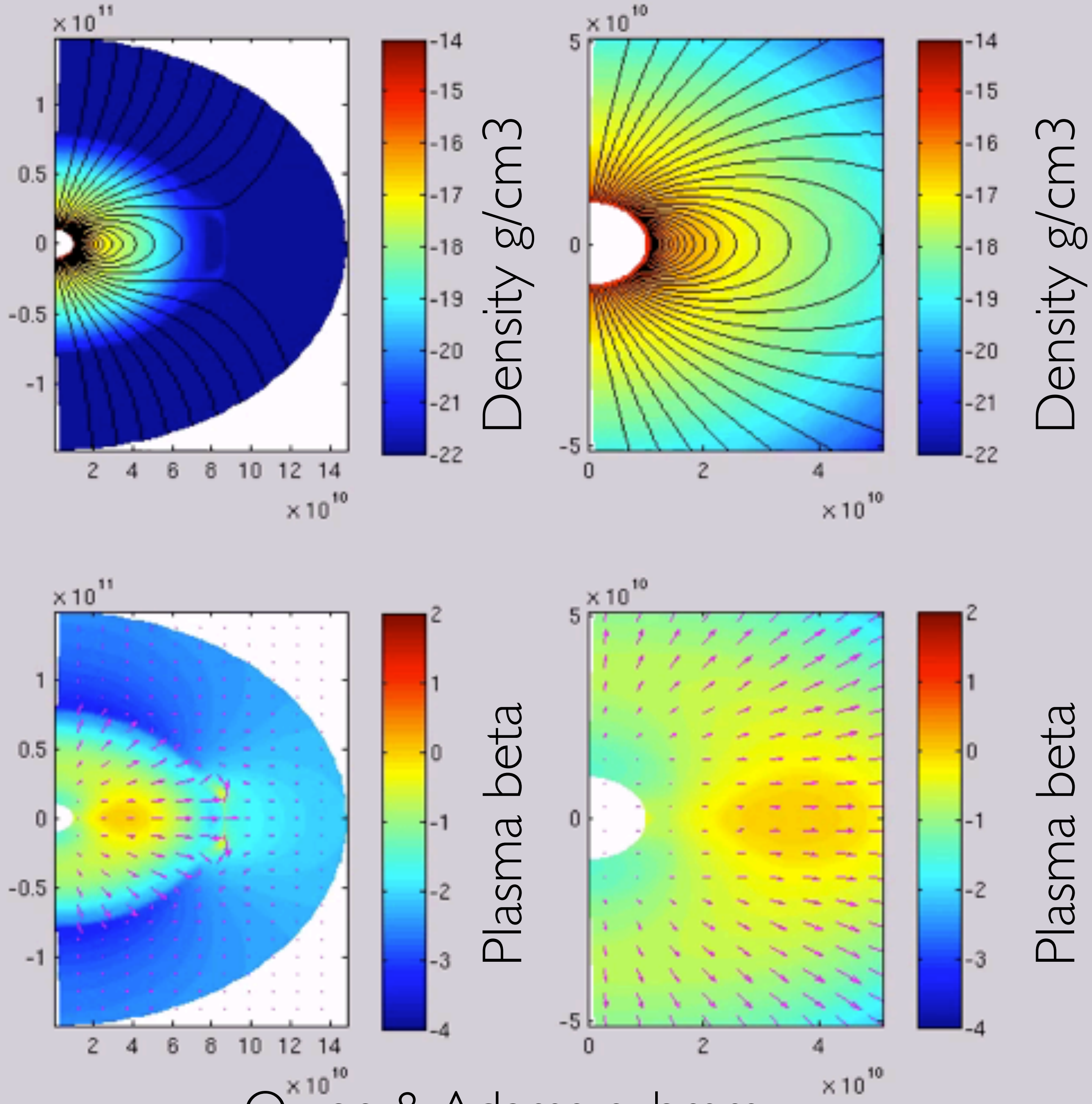




Magnetic structure near planet: dipole + stellar background

- Simple planet dipole + vertical background field from star.
- Magnetic topology perpendicular to pure hydro flow topology near planet.
- Flow highly ionized, will couple to field.
- Flow must follow field, either break dipole field topology or follow it.

ROLE OF MAGNETIC FIELDS (2)

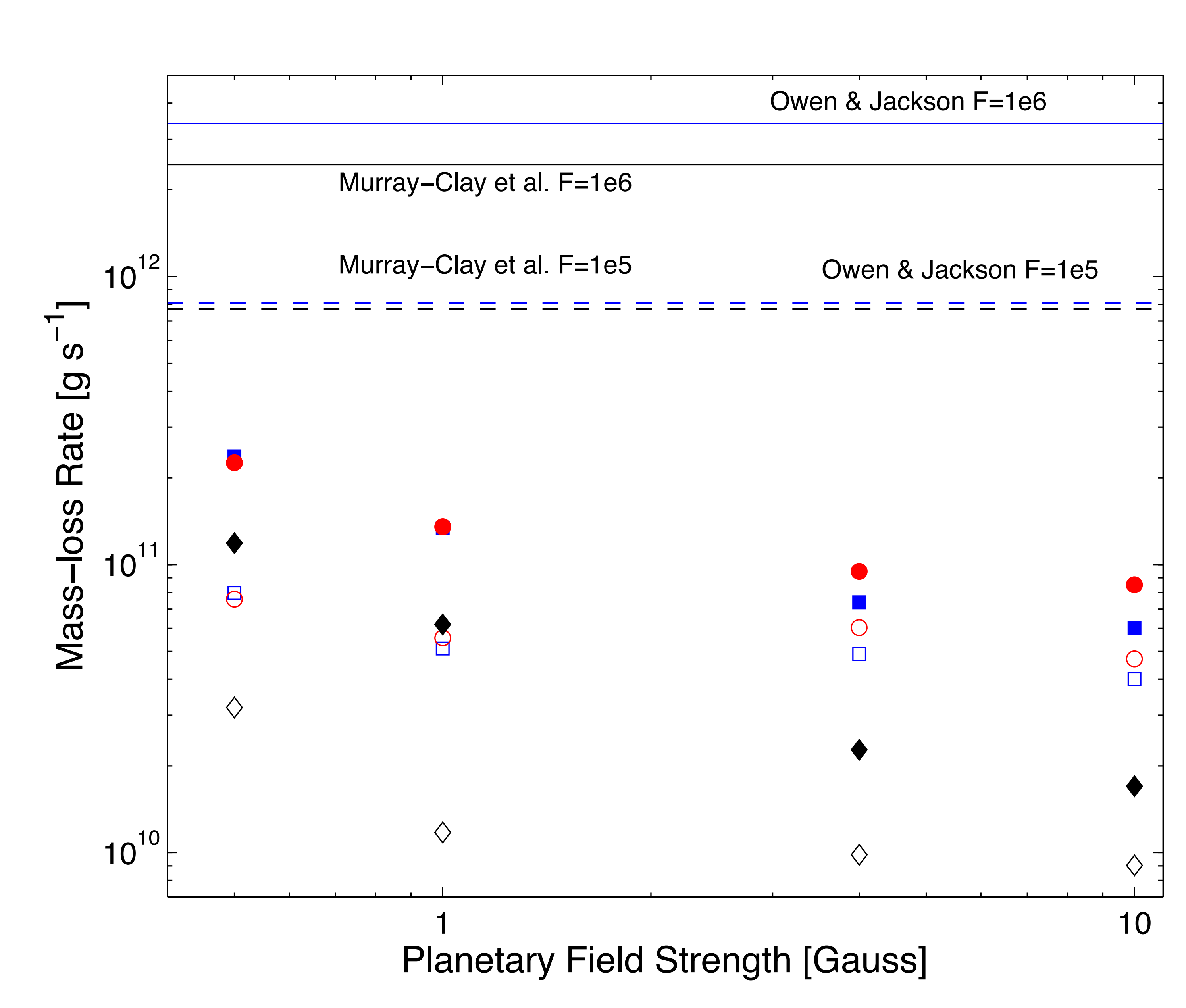


Owen & Adams, submm

- Jupiter Mass planet with field of 0.1Gauss (~low) at 0.05 AU from a young sun-like star

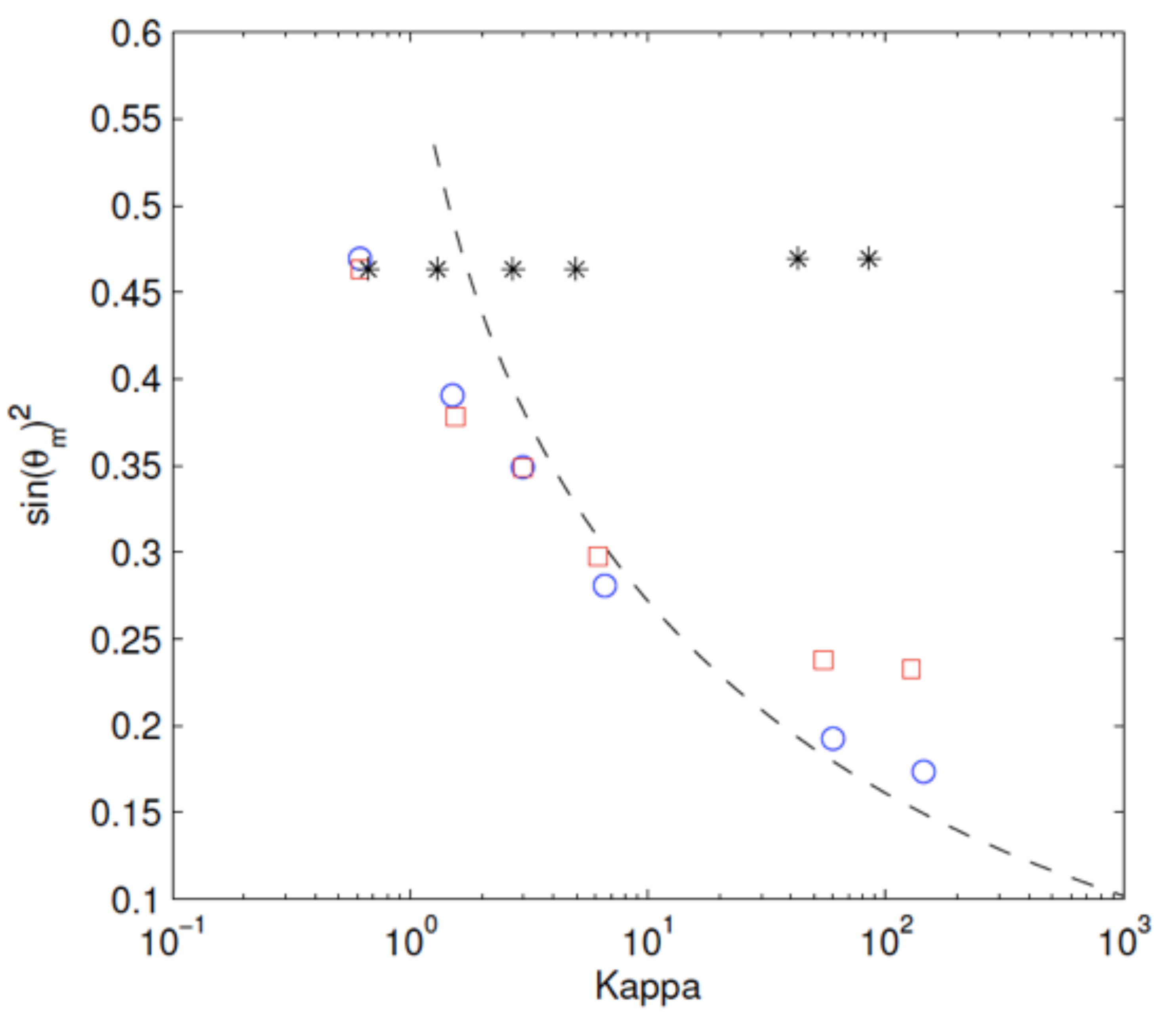
- Flow unable to open out closed field lines. For Jupiter Mass planets B fields important…

SUPPRESSION OF MASS-LOSS BY B FIELD FOR JUPITERS



- Magnetic field suppresses mass-loss rate by approximately 1 order of magnitude.
- Due to fact mass-loss comes from only day side and only from poles.

AMOUNT OF FLOW SHUT OFF

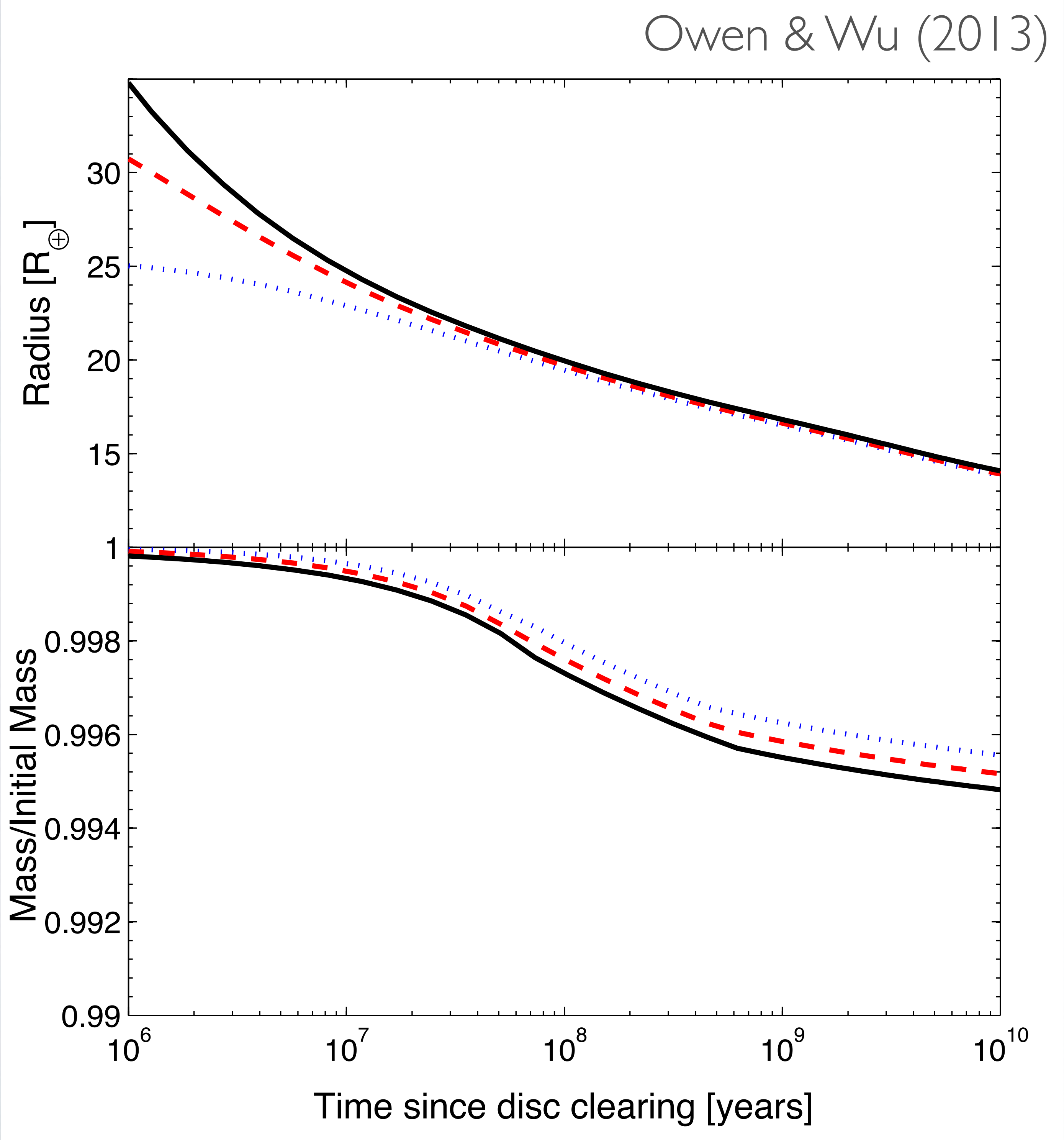


- Amount of open field lines (flow) set by ratio of magnetic to thermal pressure (Kappa), for Jupiters need a field > 0.1 Gauss.
- For Neptunes need a field > 5 Gauss, so unclear whether low-mass planets will be magnetically controlled.

EXOPLANET EVOLUTION

- Coupled (non-magnetic) mass-loss rates to the MESA stellar evolution code (Paxton et al. 2011).
- Include bolometric irradiation from central star, solid core which can be a heat source due to heat capacity and radioactive-decay. Code modifications by Owen & Wu (2013)
- Model the evolution of a H/He envelope on top of solid core under the influence of evaporation.

JUPITER LIKE PLANETS



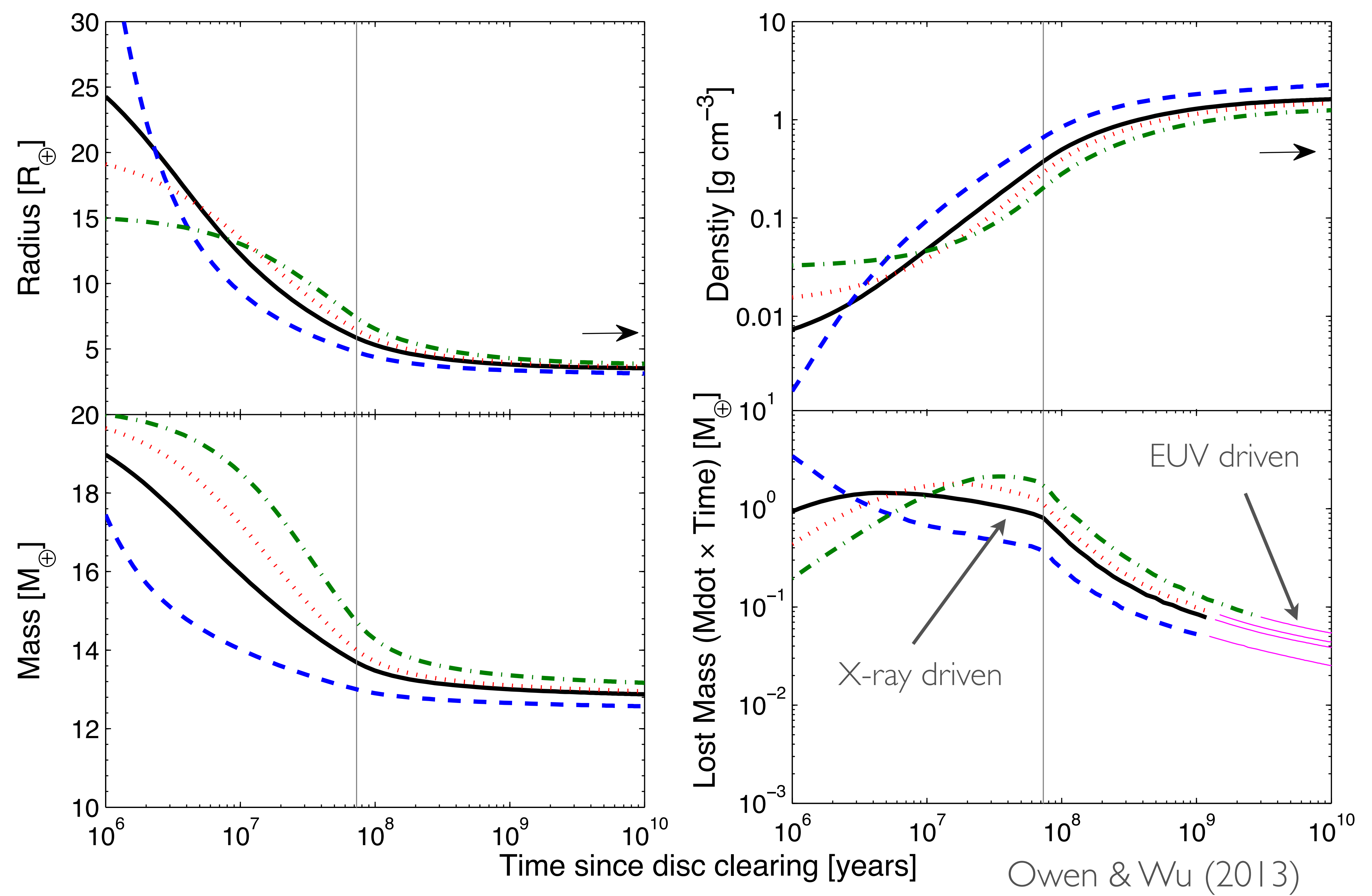
- Limited knowledge of initial entropy requires modelling a range of initial entropies.

- Parameterise initial entropy in terms of initial cooling time 1e6-1e8 yrs.

- Mass-loss at the <1% level for very close separations 0.025AU.

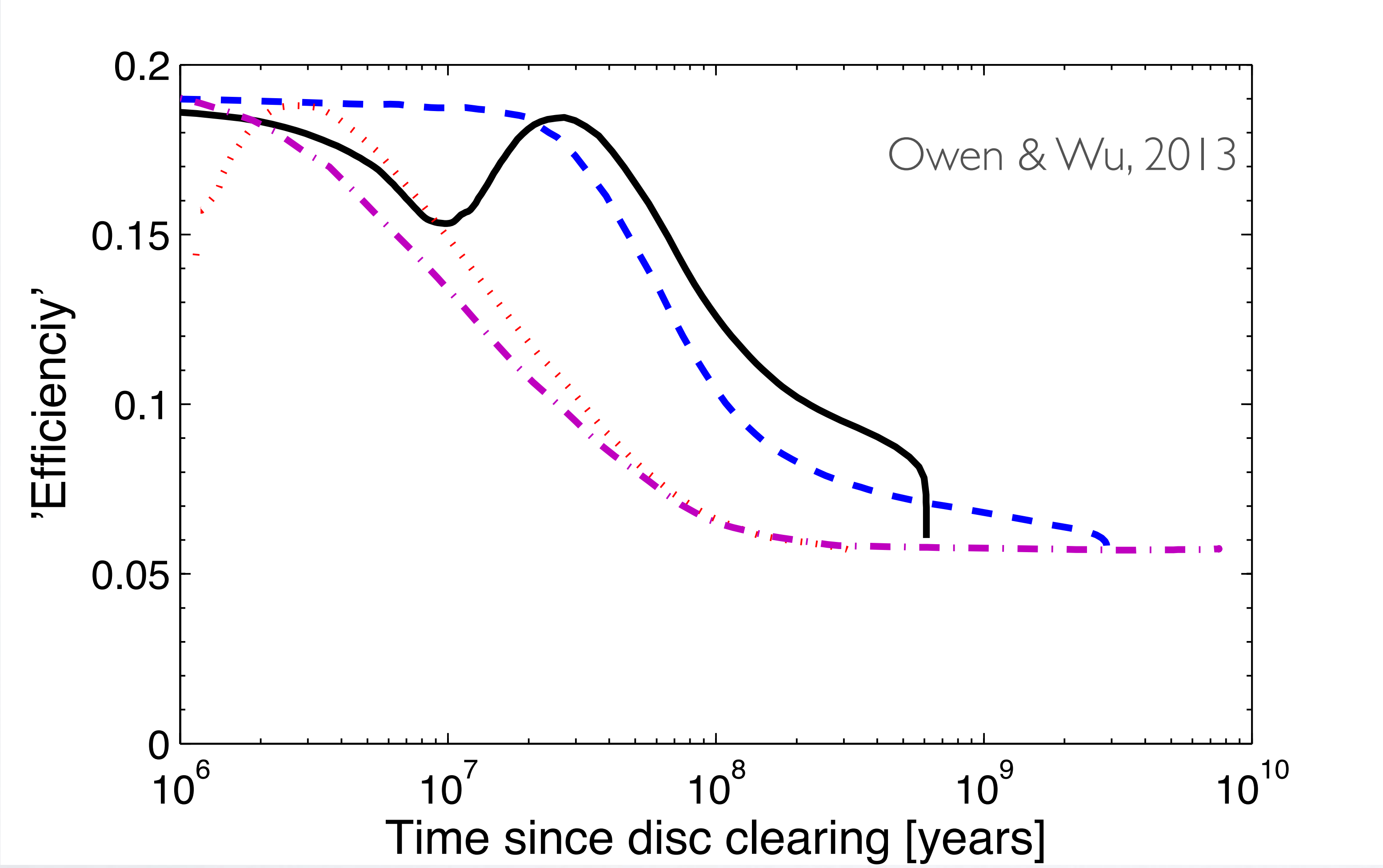
LOW MASS-PLANETS

- Initially 20 Earth mass planet with 12.5 Earth mass core at 0.05 AU



Owen & Wu (2013)

`EFFICIENCY' EVOLUTION

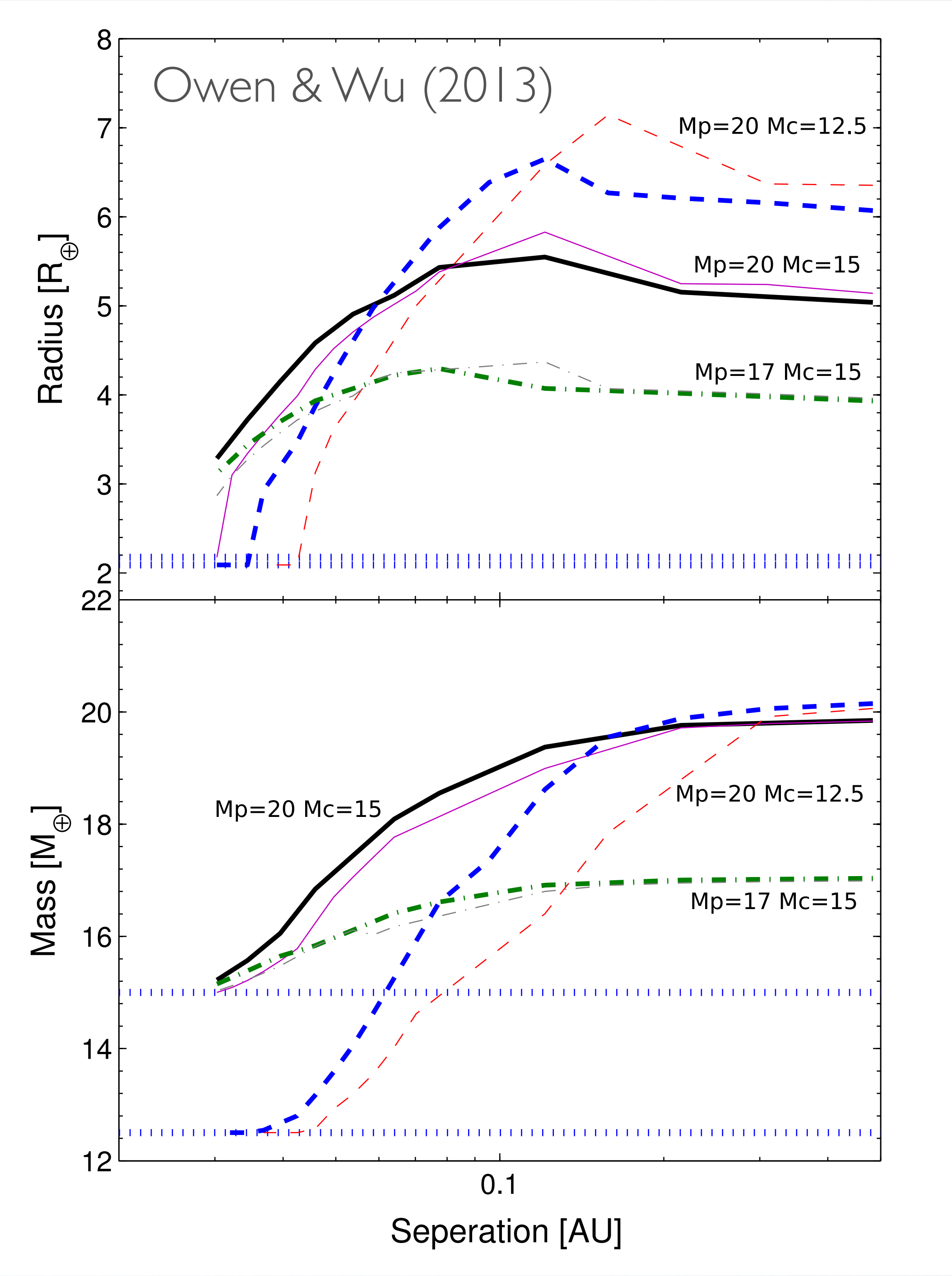


Initially 20 Earth mass planets at separations of 0.15, 0.1 ,0.075 & 0.05 AU

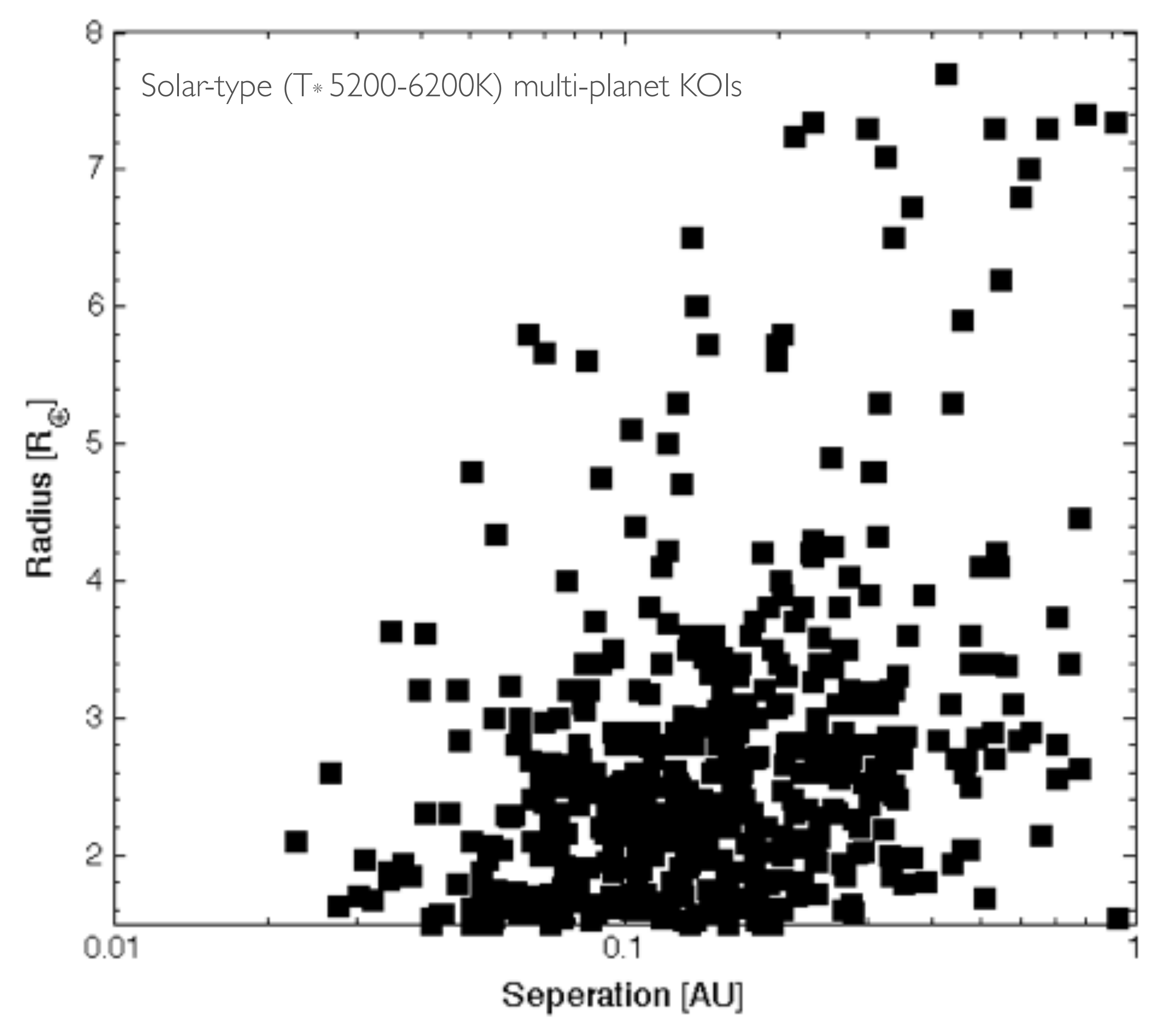
- Efficiency generally decreases with time, although evolution is not in general monotonic.
- Average value of ~10% for low-mass planets qualitatively reproduces populations (Lopez & Fortney, 2013)

LOW MASS PLANETS (2)

- Low mass planets evolution driven by evaporation.
- Mass-loss strongly sensitive to separation inside ~0.2 AU
- At closest separations entire H/He can be removed.
- Mass-loss primarily sensitive to core-mass.

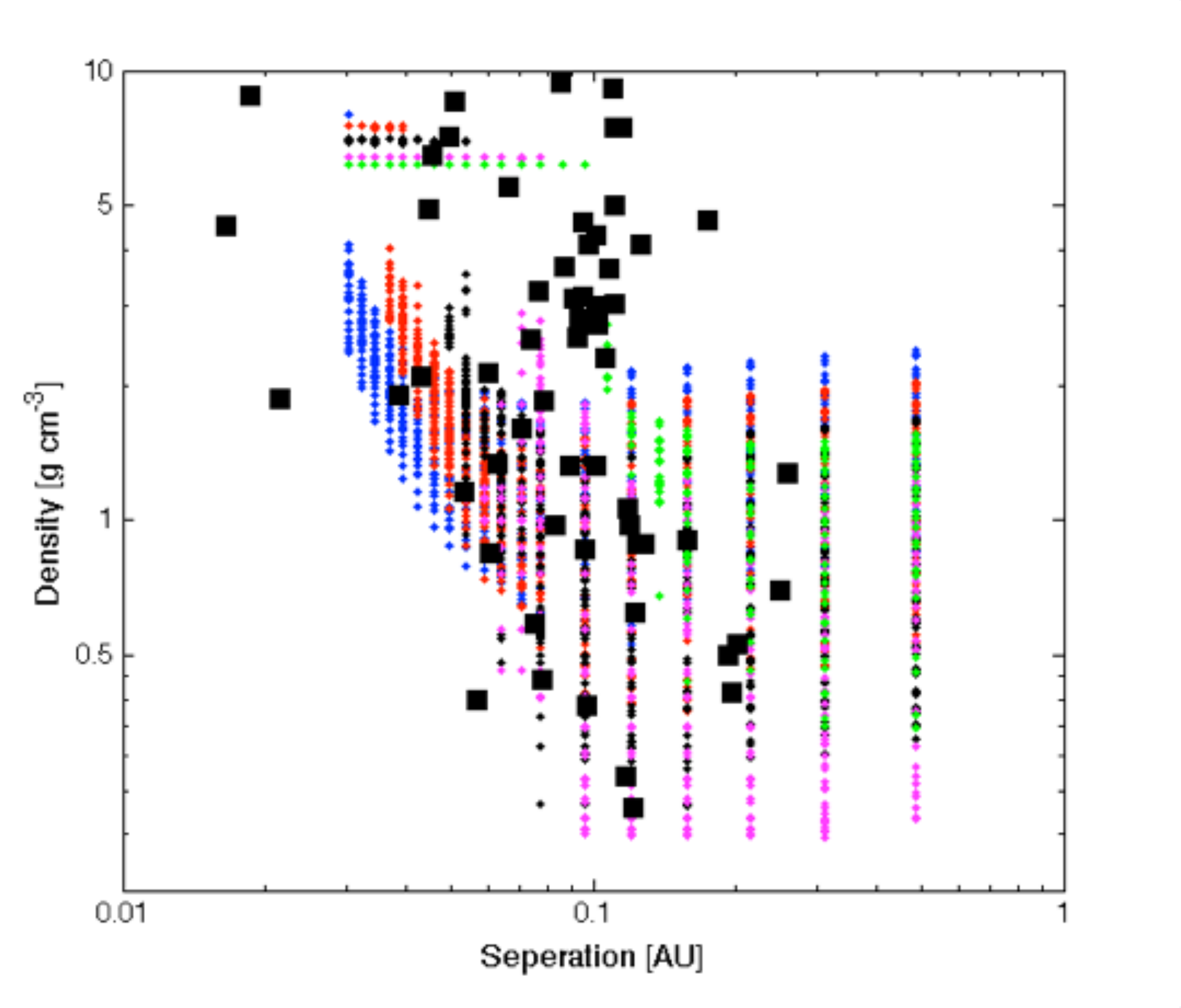


MAXIMUM MASS FOR LOW-MASS PLANETS



- Planet radius distribution with separation, shows lack of large planets at small separation.
- Envelope shows similar distribution to the evaporation evolution with separation.

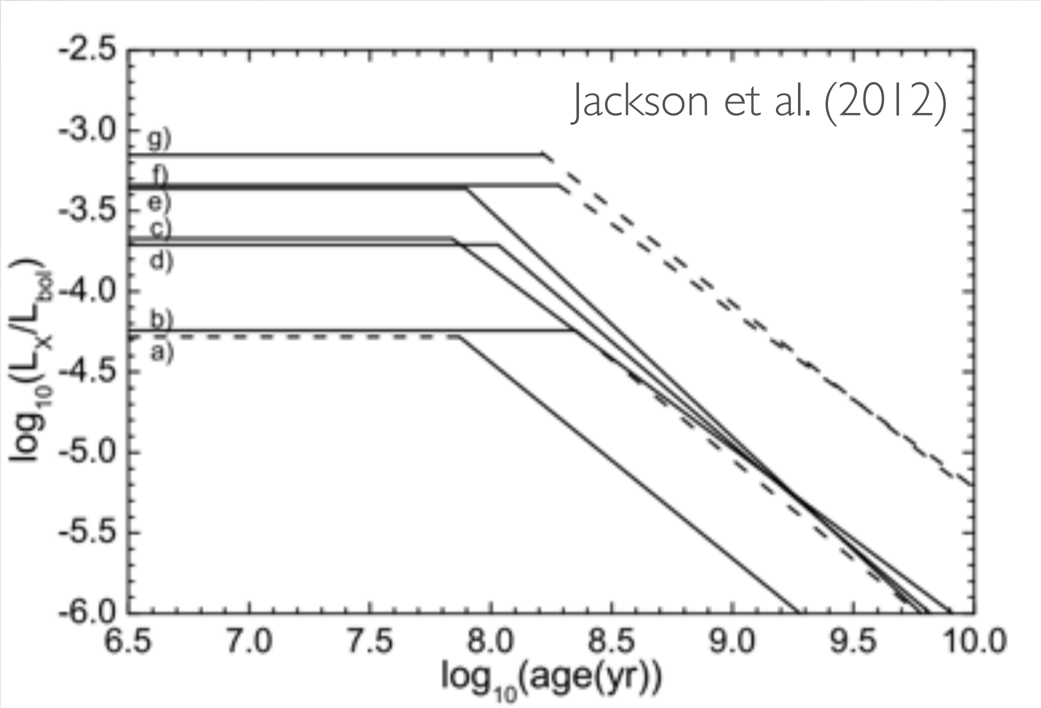
MAXIMUM MASS FOR LOW-MASS PLANETS (2)



Owen & Wu 2013

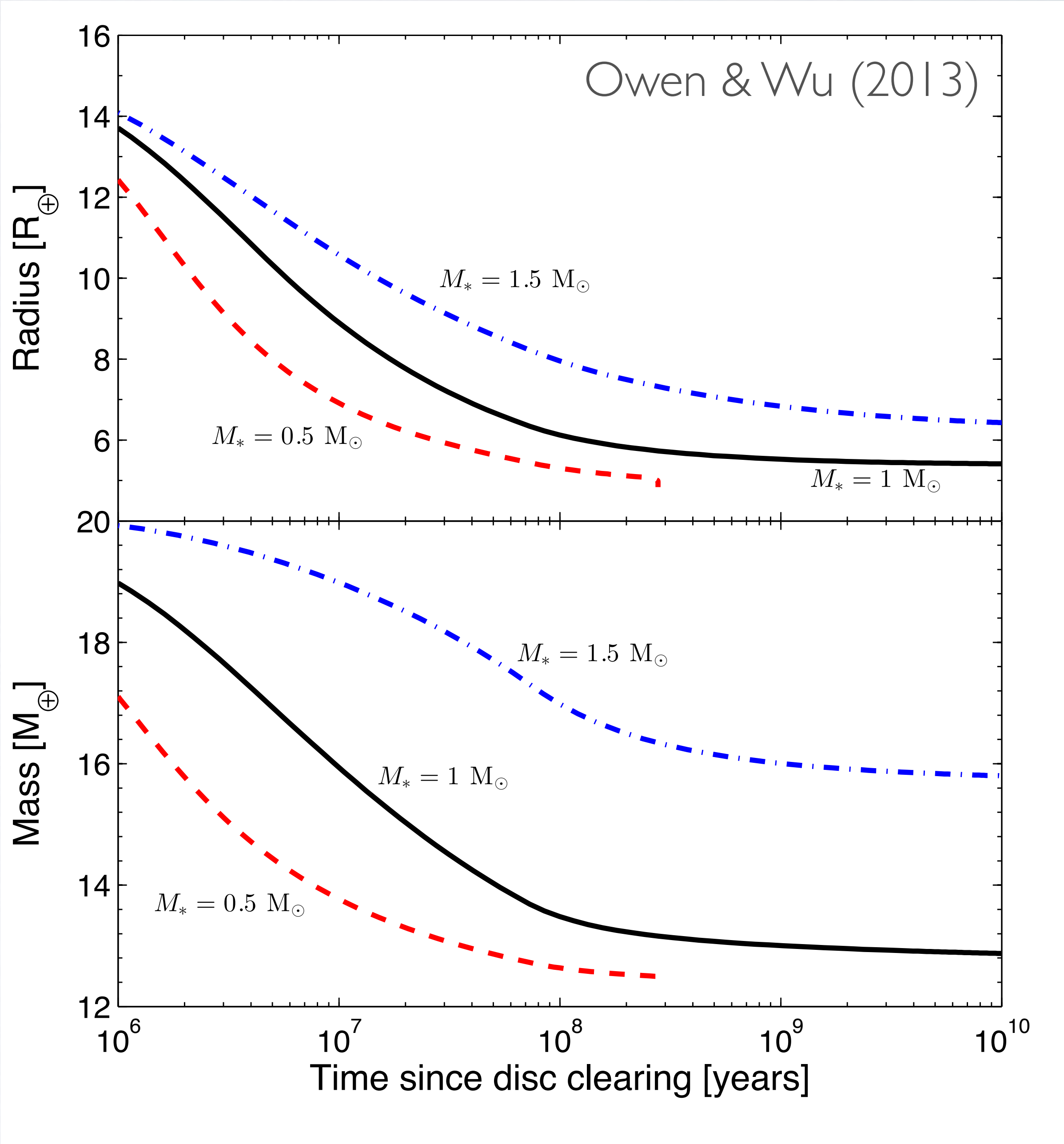
- Planet population with Mp<20M⊕ and rocky cores with masses 10-15M⊕ fits envelope.
- Same population also fits the density distribution of low-mass planets.

VARIATIONS WITH STELLAR MASS


Jackson et al. (2012)

- Planets around late type stars experience higher X-ray fluxes for longer.

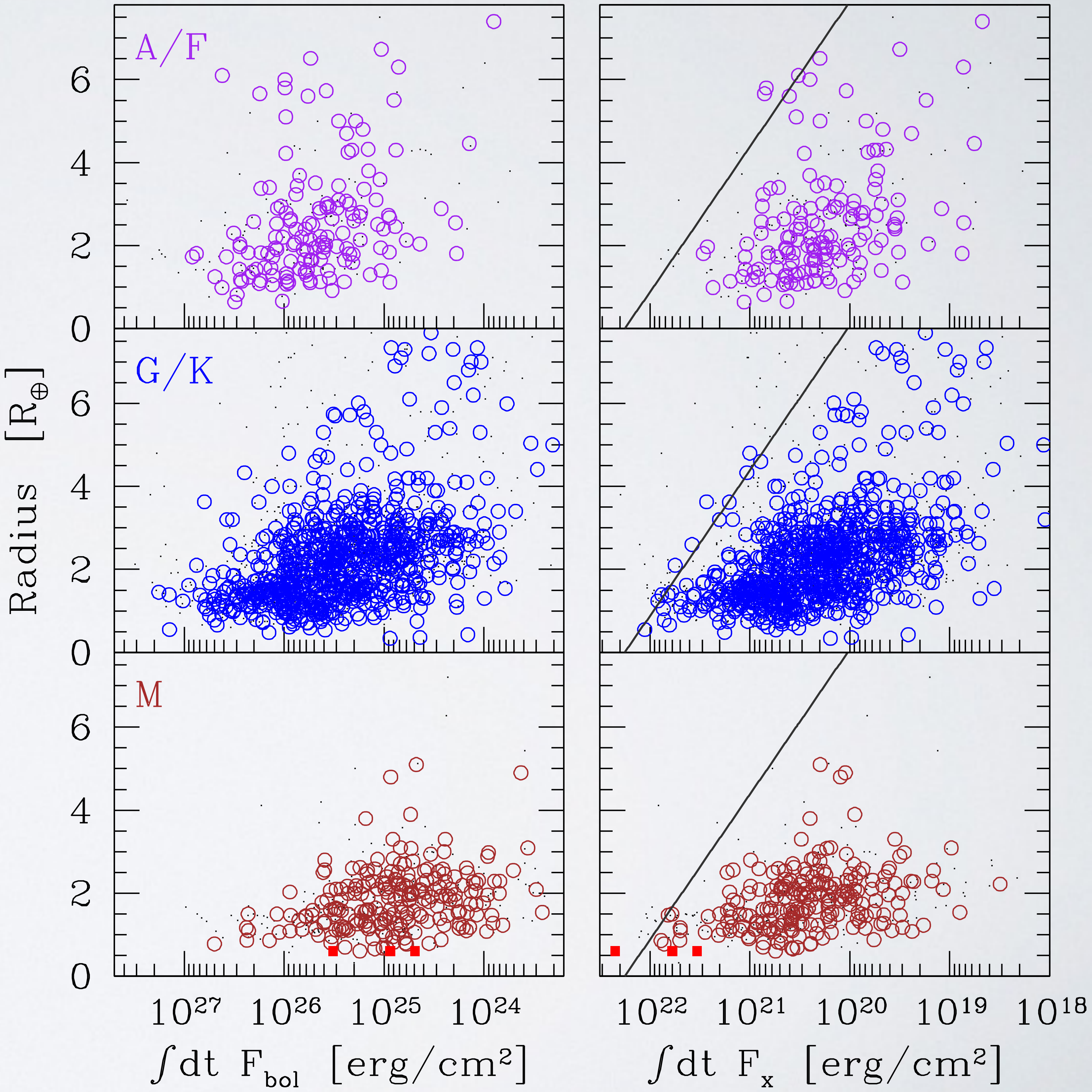
- Evaporation even more important around low-mass stars.


Owen & Wu (2013)

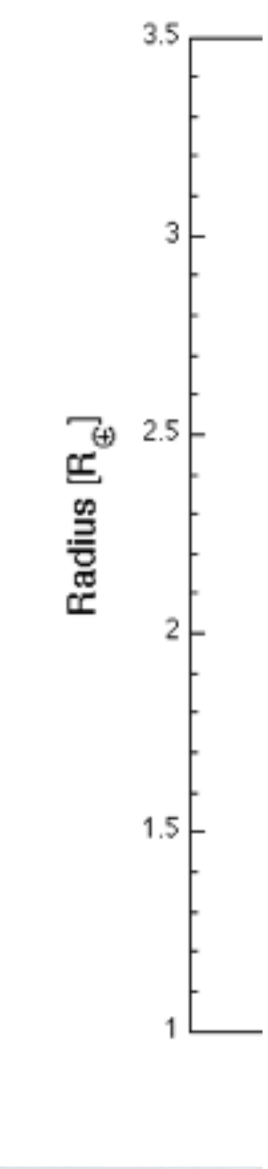
VARIATIONS WITH STELLAR MASS

- Lack of large radius planets at high effective temperatures depends strongly on stellar mass.
- However if re-scale in terms of X-ray `exposure' then lack of large radius planets coincident across all stellar types.
- Good evidence X-ray evaporation controlling evolution of low-mass exoplanets.

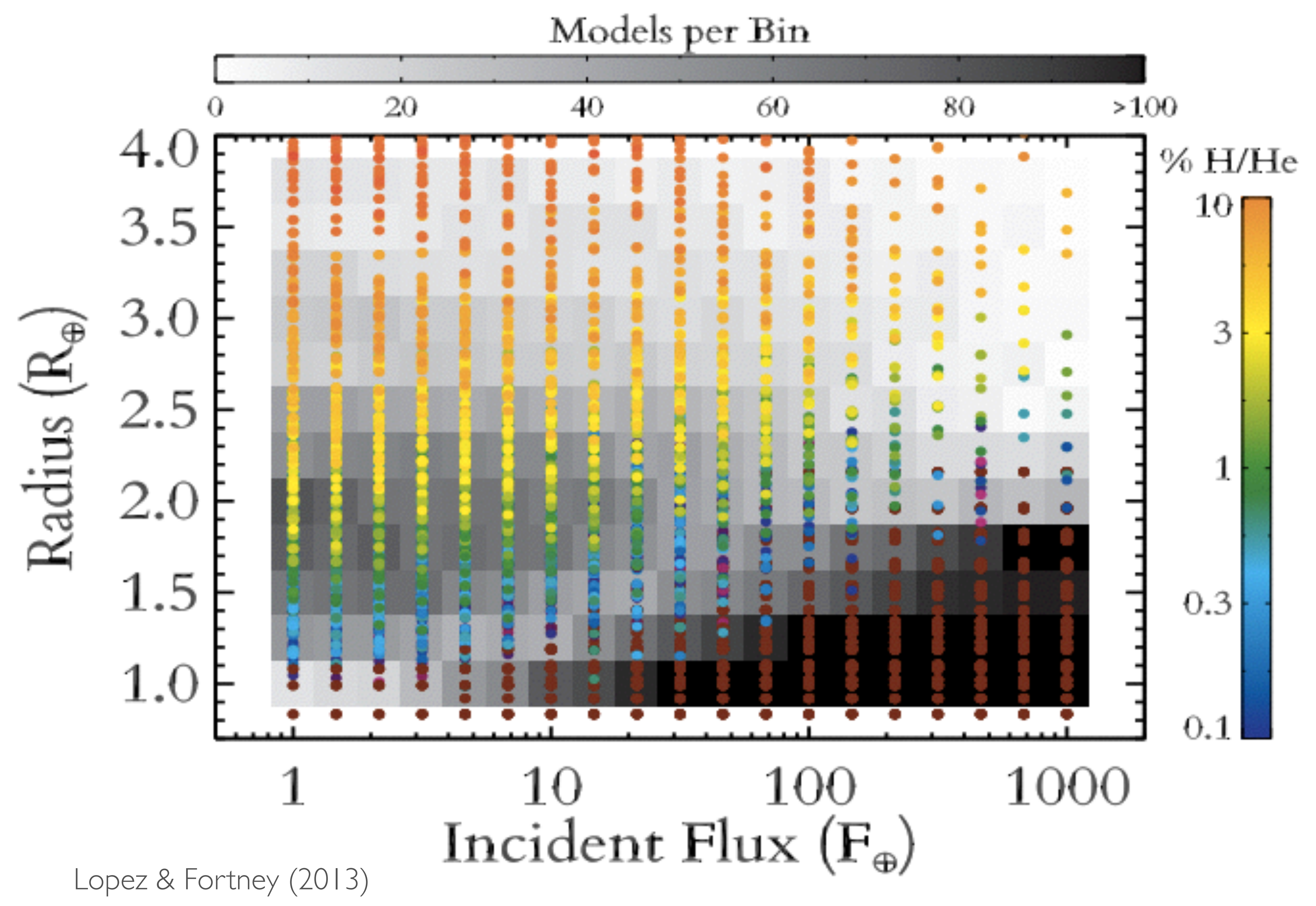
Owen & Wu (2013)



A GAP IN THE RADIUS DISTRIBUTION?

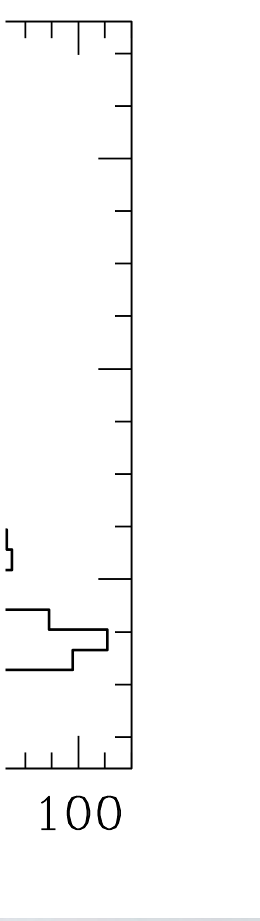


Owen & Wu



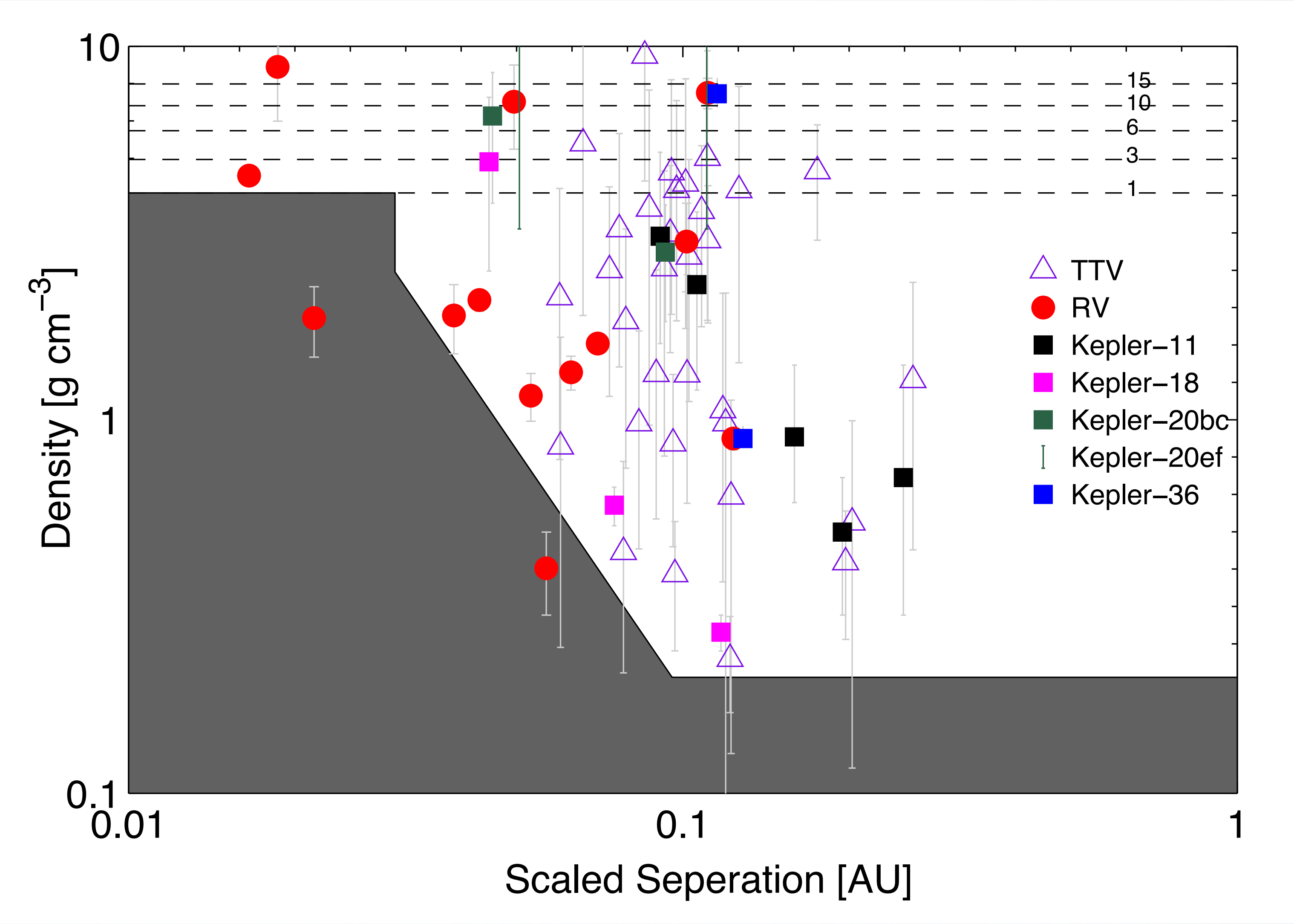
Lopez & Fortney (2013)

ant 2
high/
rcent



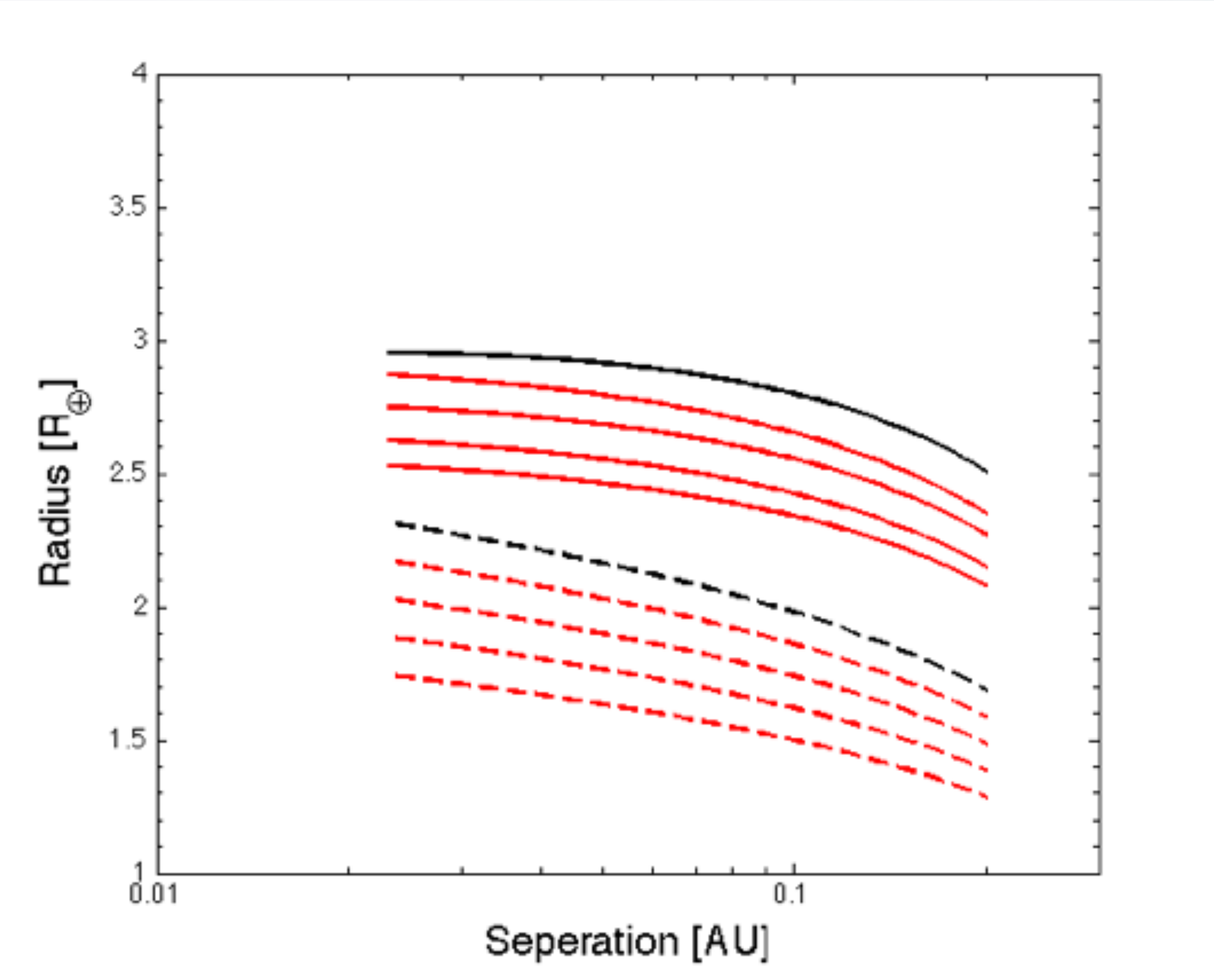
DENSITY DISTRIUBTION

- Unlike radius distribution expect no gap in the density (or mass) distribution.
- Naked lower mass cores or rocky planets fill in the any gap.
- Gap would be easiest to detect in radius distribution.



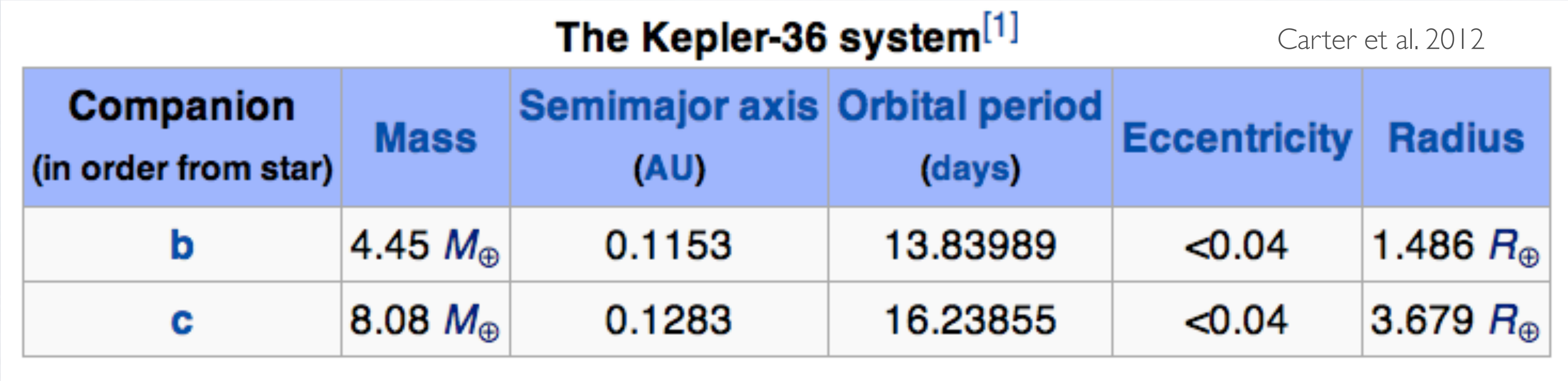
CORE COMPOSITION FROM GAP

- Position and structure of the gap sensitive to underlying core density
- If gap is detected in the exoplanet data can learn about core composition - formation origins of cores
- However if cores contain a large spread ice fraction than gap can be washed out.



FUTURE DIRECTION

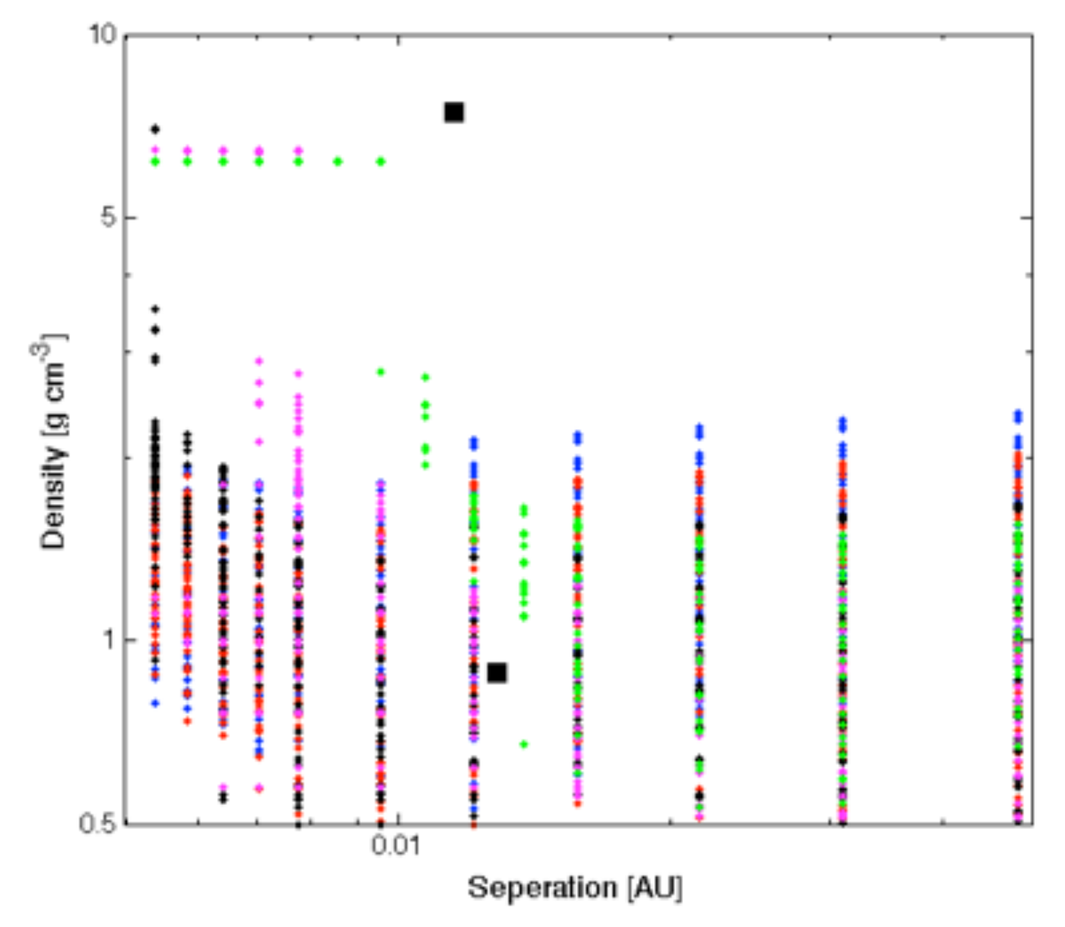
APPLICATION TO INDIVIDUAL SYSTEMS AND BEYOND.



The Kepler-36 system[1]

Carter et al. 2012

Companion (in order from star)	Mass	Semimajor axis (AU)	Orbital period (days)	Eccentricity	Radius
b	4.45 $M_\oplus$	0.1153	13.83989	<0.04	1.486 $R_\oplus$
c	8.08 $M_\oplus$	0.1283	16.23855	<0.04	3.679 $R_\oplus$



- Models require 36c to have a 6.5-7.5 M⊕ core with ~1 M⊕ of H/He
- Models require 36b to have a core <6 M⊕ to loose a primordial envelope.

SUMMARY

- Hydrodynamic evaporation driven by the X-rays at early times is particularly important for the evolution of Hydrogen rich low-mass planets.

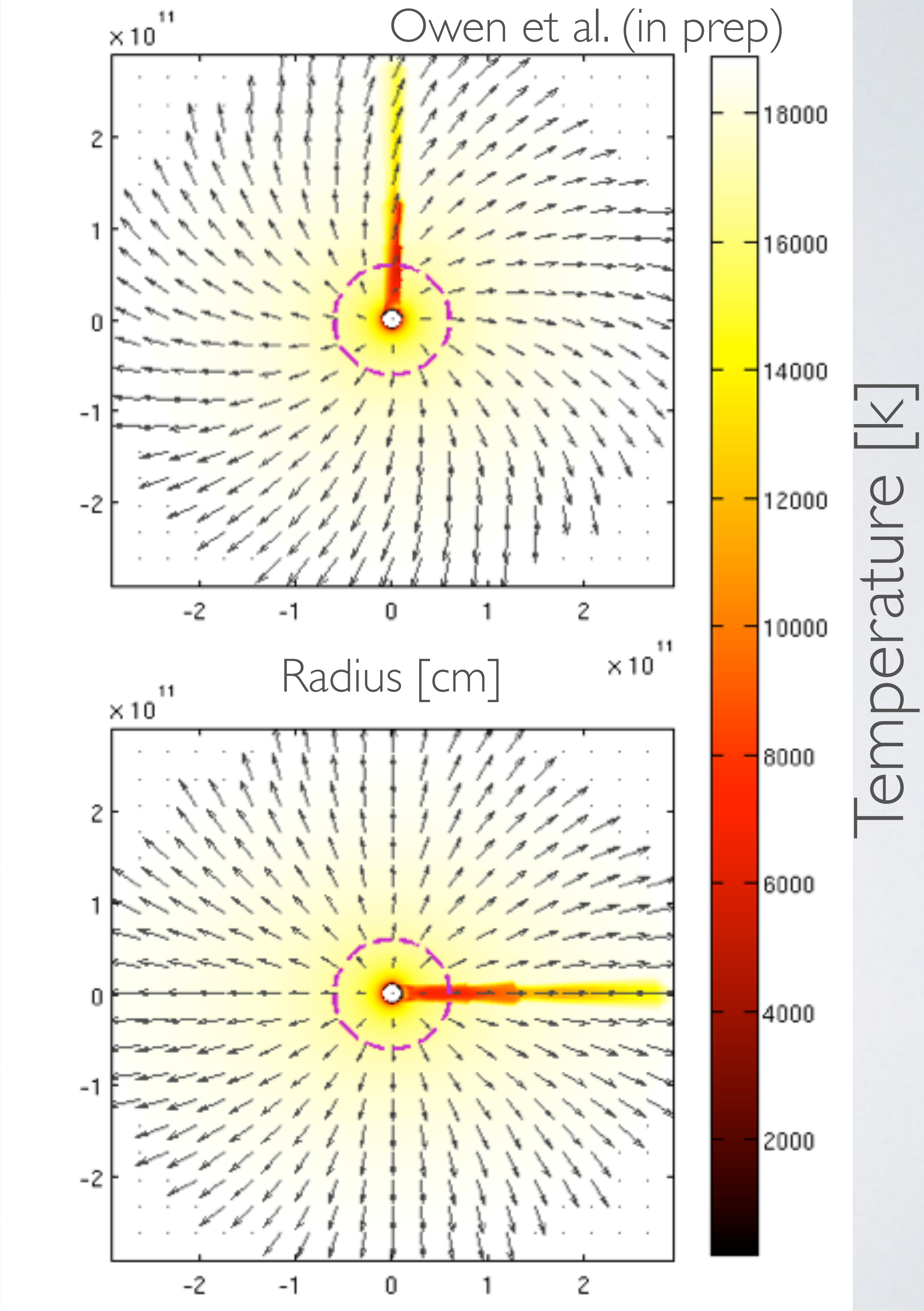
- Sculpting of the observed planet population by evaporation suggests a maximum mass for low mass planets of 20 $M_\oplus$

- Comparison with the Kepler radius distribution suggests most planets have experienced significant evaporation during their lifetime, with up to 50% having had H/He envelopes removed.

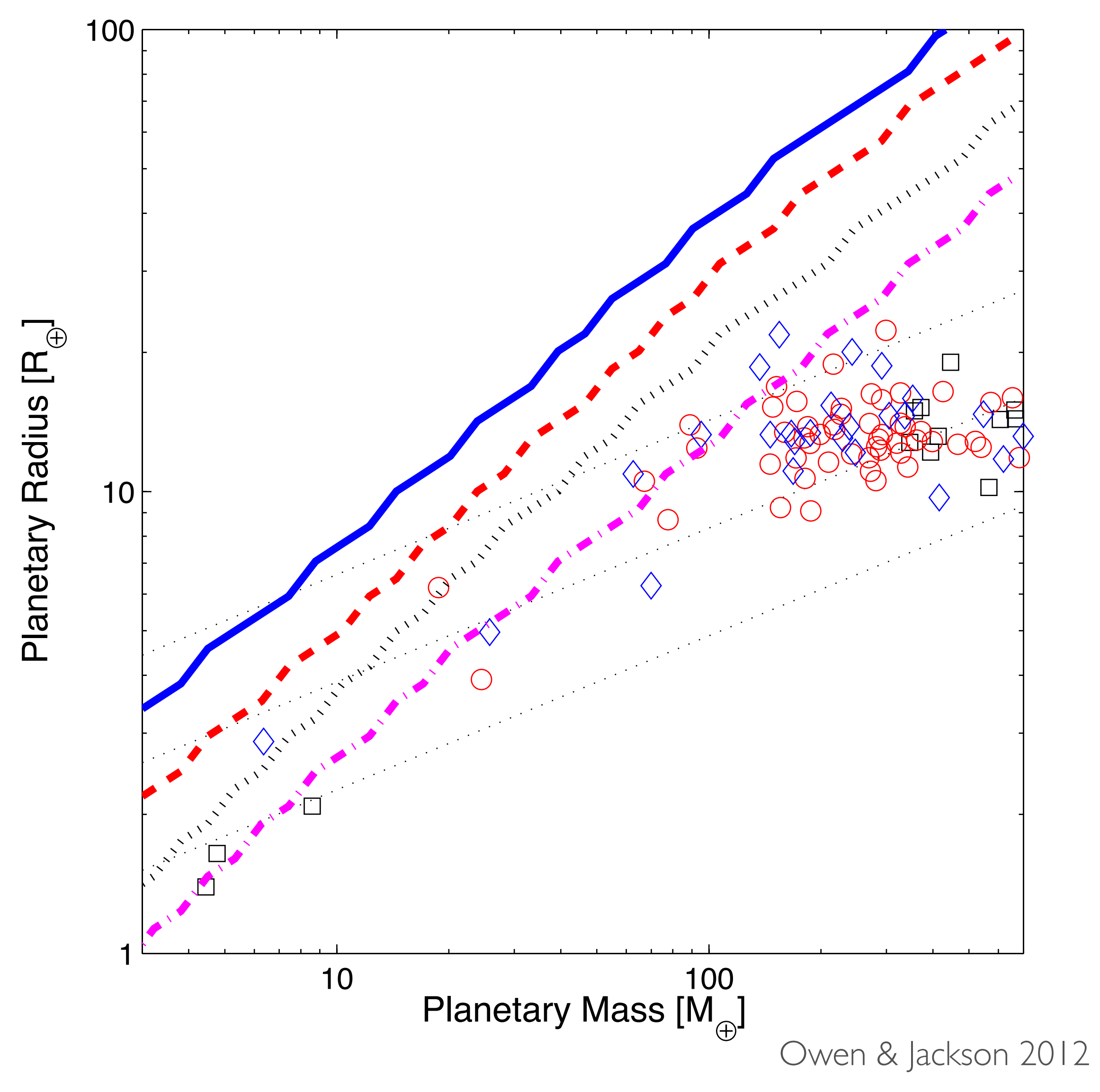
- Future direction: Use evolution models with evaporation to infer properties of exoplanet population at birth and extend models to more exotic compositions.

3D MODELS-WORK IN PROGRESS

- Simple X-ray only 3D model, no rotation, simple cooling rate.
- 1D Mdot~3e11g/s compared to 3D Mdot~ 2.2e11g/s



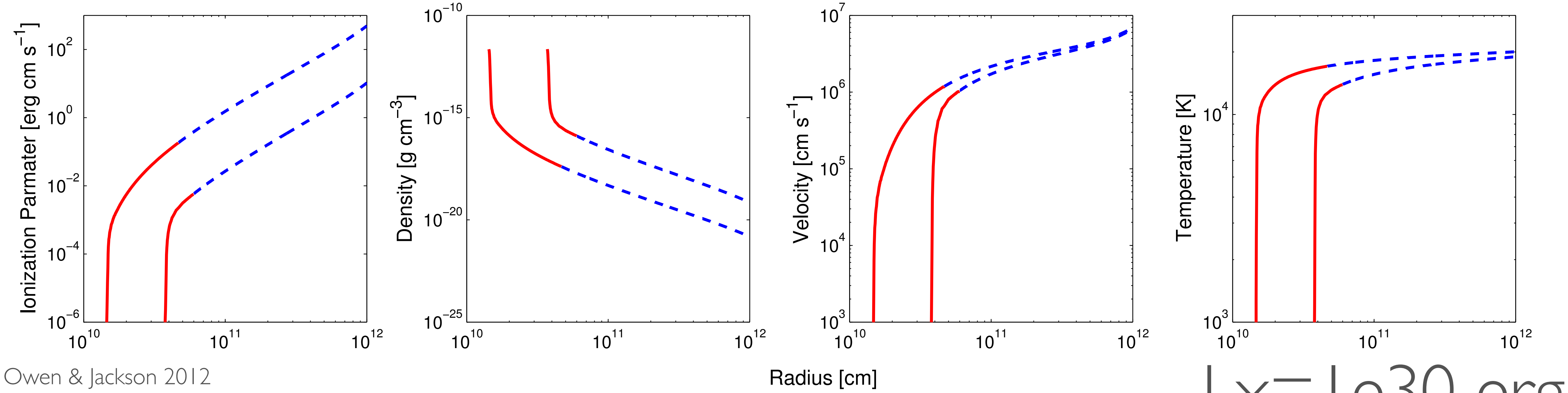
EVAPORATING CLOSE IN PLANETS



Owen & Jackson 2012

Low mass planets, appear to be prone to significant evaporation and possibly entire loss of their atmosphere.

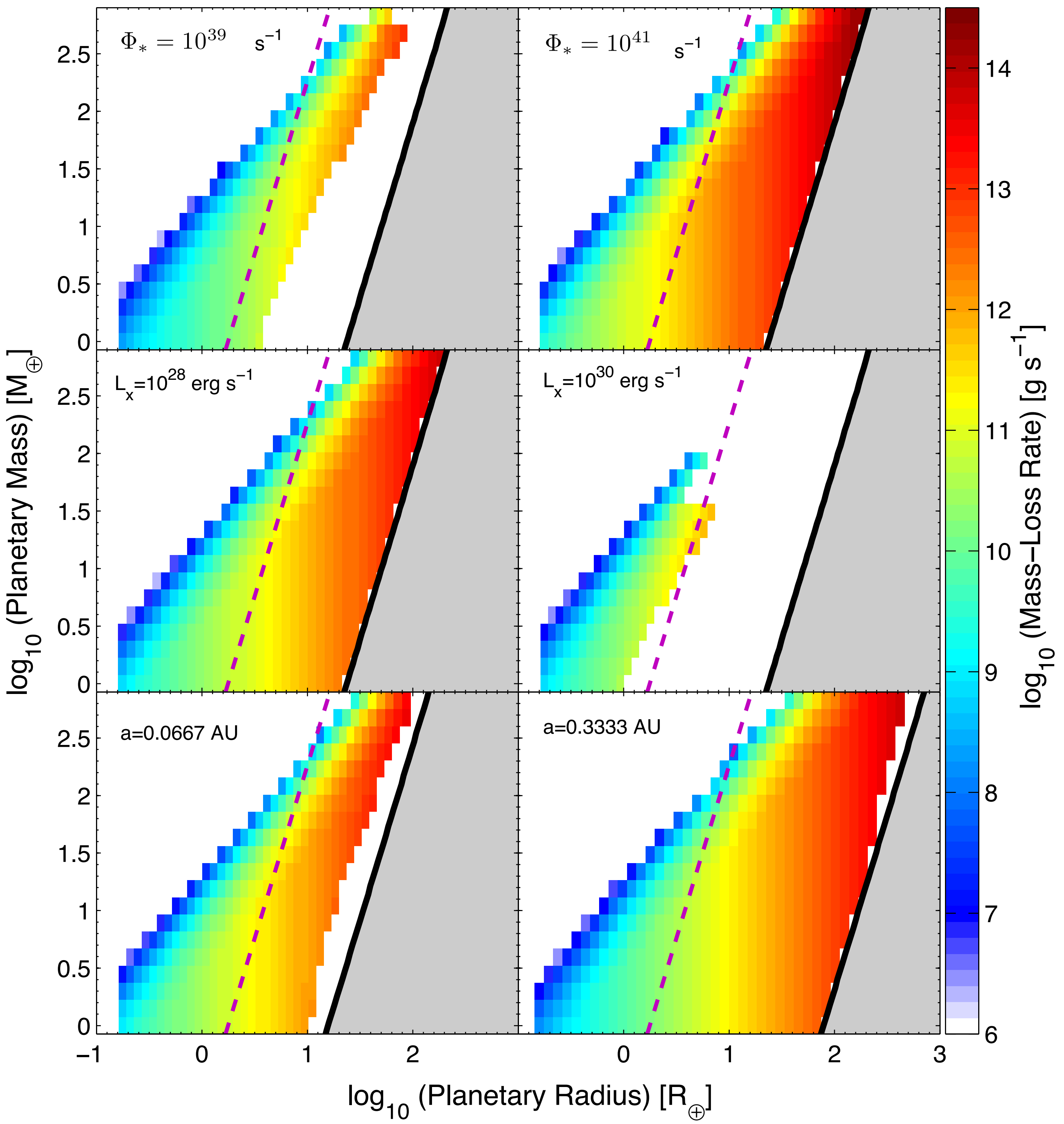
X-RAY DRIVEN EVAPORATION

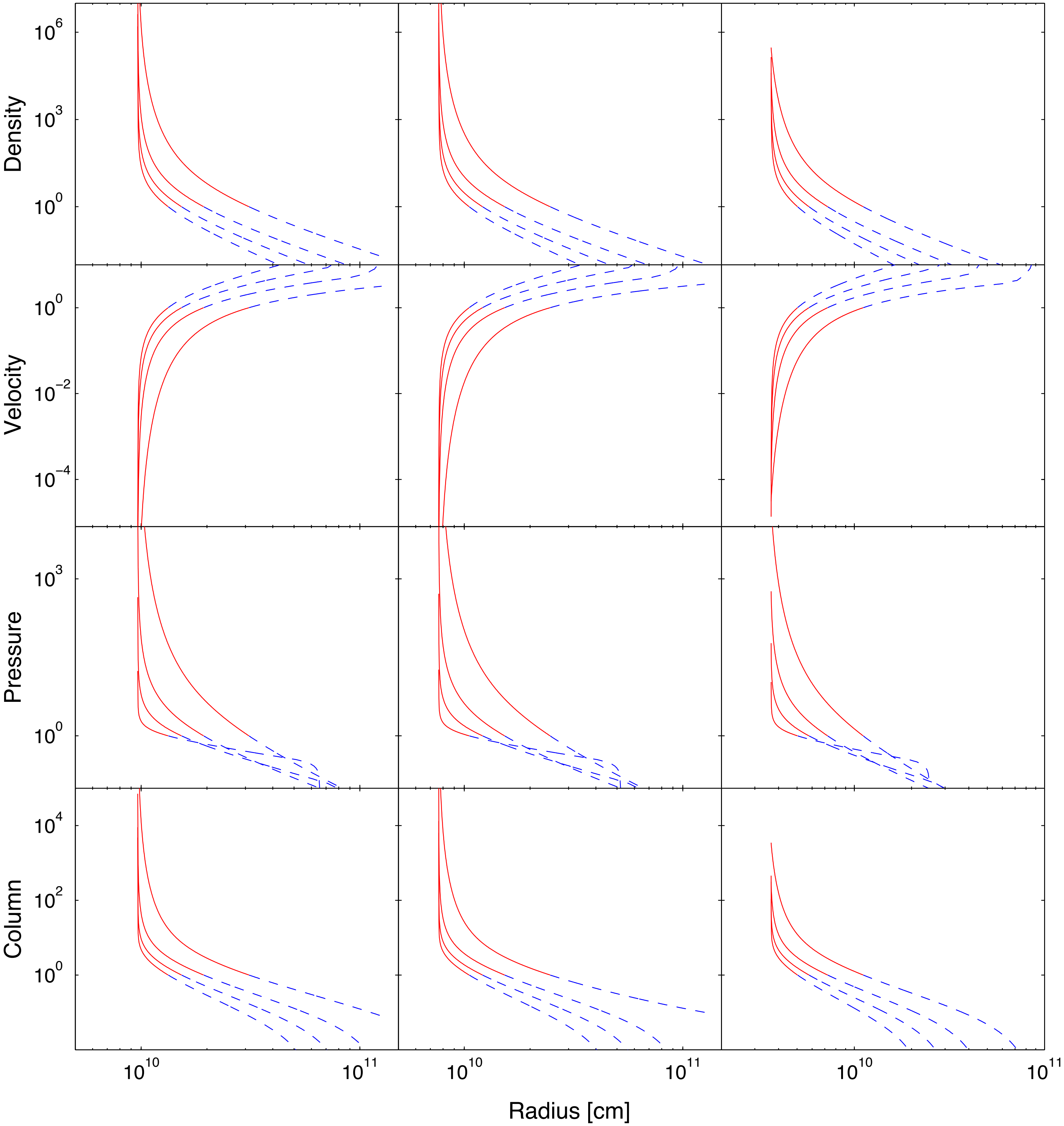


Owen & Jackson 2012

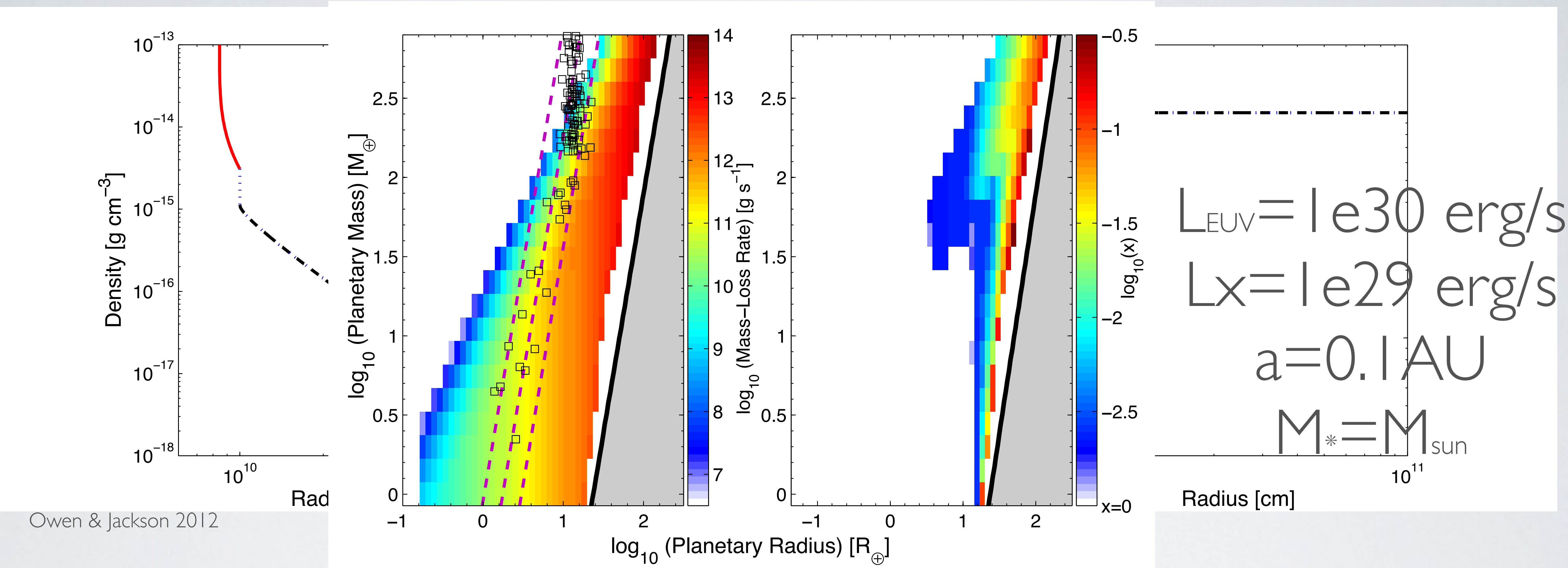
Lx=1e30 erg/s
a=0.1AU
$M_{*}=M_{sun}$

- Step pressure gradients close to planet.
- Sonic surface in constrained to within a few planetary radii
- Flow isothermal at large radius


$\Phi_* = 10^{39}$ s^{-1}
$\Phi_* = 10^{41}$ s^{-1}
L$_x$=10^{28} erg s^{-1}
L$_x$=10^{30} erg s^{-1}
a=0.0667 AU
a=0.3333 AU
0
0.5
1
1.5
2
2.5
log$_{10}$ (Planetary Mass) [M$_\oplus$]
−1
0
1
2
3
log$_{10}$ (Planetary Radius) [R$_\oplus$]
6
7
8
9
10
11
12
13
14
log$_{10}$ (Mass−Loss Rate) [g s^{-1}]


Density
10^6
10^3
10^0
Velocity
10^0
10^{-2}
10^{-4}
Pressure
10^3
10^0
Column
10^4
10^2
10^0
10^{10}
10^{11}
10^{10}
10^{11}
10^{10}
10^{11}
Radius [cm]

EUV EVAPORATION

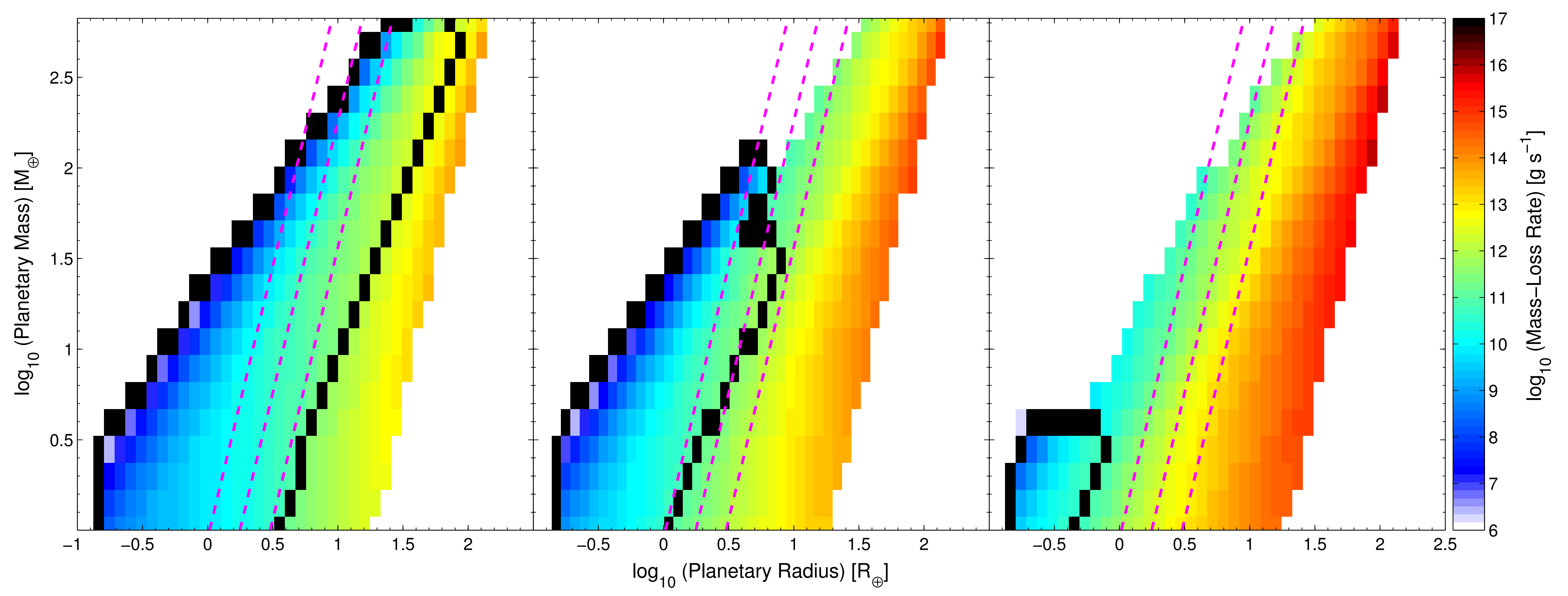


L_{EUV}=1e30 erg/s
Lx=1e29 erg/s
a=0.1AU
$M_*=M_{sun}$

Owen & Jackson 2012

- Small sub-sonic X-ray heated region, which transitions to EUV heated region through ionization front.

- EUV rates are lower than X-ray rates, dominates for smaller planets, larger separations and lower luminosities.


log₁₀ (Planetary Mass) [M⊕]
0.5
1
1.5
2
2.5
−1
−0.5
0
0.5
1
1.5
2
2.5
log₁₀ (Planetary Radius) [R⊕]
log₁₀ (Mass−Loss Rate) [g s⁻¹]
6
7
8
9
10
11
12
13
14
15
16
17